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Evidence for an anomalous like-sign dimuon charge asymmetry

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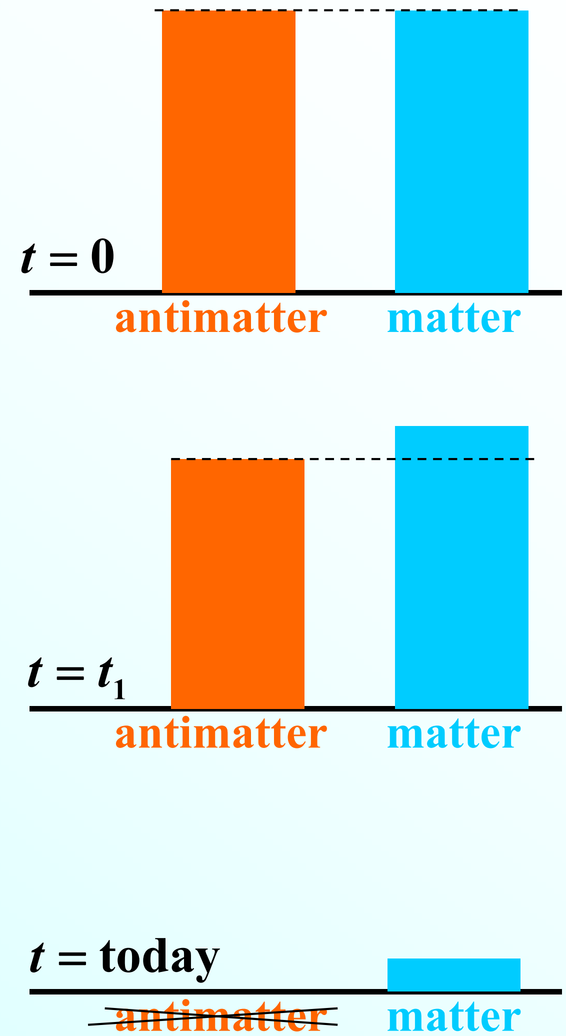
Matter – Antimatter Asymmetry

- One of major challenges of particle physics – explain the dominance of matter in our Universe
- Number of particles and antiparticles produced in the Big Bang is expected to be equal
- For some reason matter becomes more abundant in the early stages of Universe
- Antimatter completely annihilated
- Hence we're left only with matter today

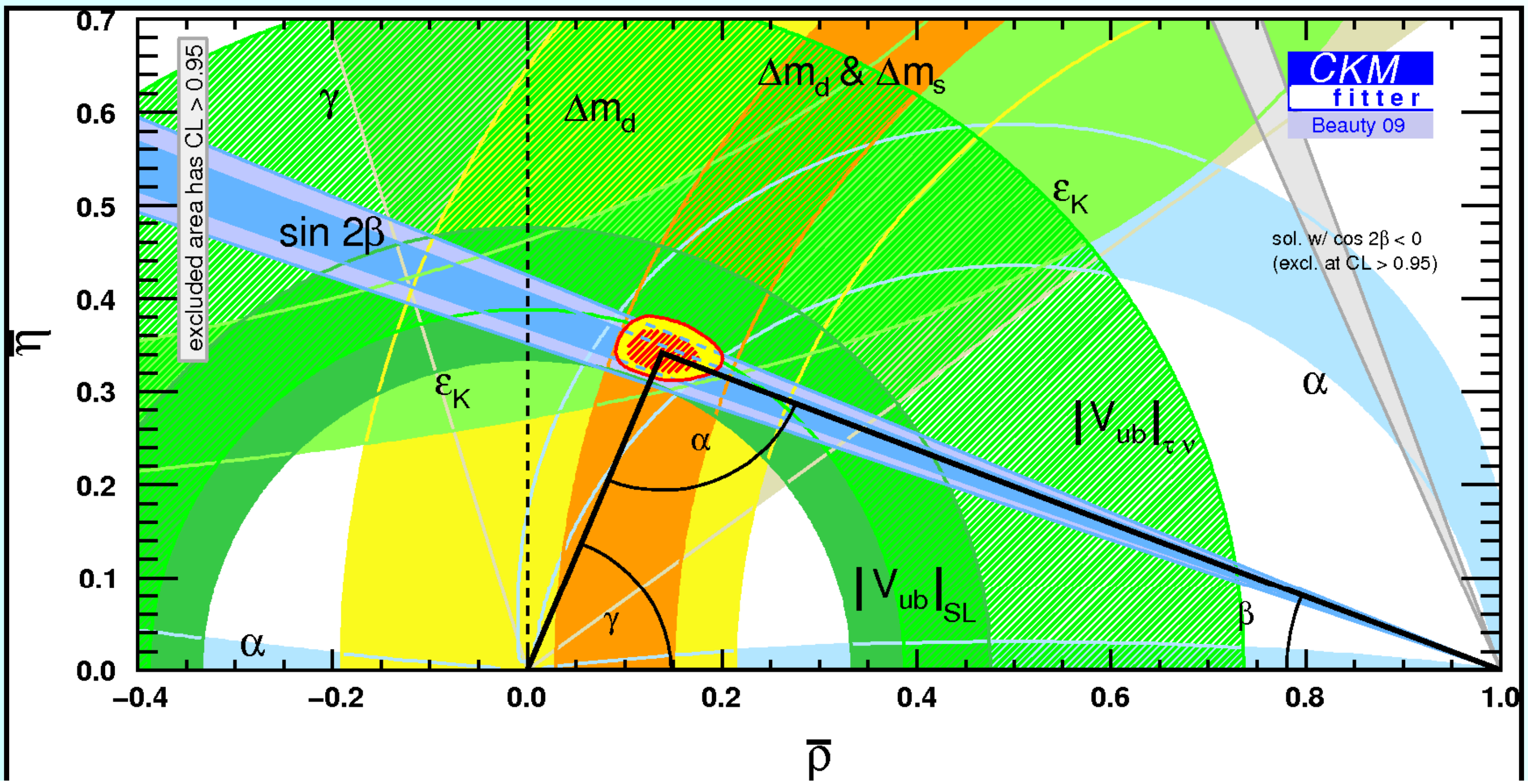


One of conditions (A. Sakharov) required to explain this process – properties of particles and antiparticles must be different

(*CP* violation)

CP violation in SM

- *CP* violation is naturally included in the standard model through the quark mixing (CKM) matrix
- Many different measurements of *CP* violation phenomena are in excellent agreement with the SM:
  - All measurements are consistent with a single apex of this unitarity triangle plot



CP violation in SM

- The SM disagrees with one experimental fact – our existence
  - The SM source of *CP* violation is not sufficient to explain the imbalance between matter and antimatter
  - See e.g. P. Suet, E. Sather, Phys.Rev.D51, 379-394 (1995)
  - Some theoretical studies claim up to 10 orders of magnitude deficit of the CP violation provided by the SM
- New sources of *CP* violation are required to explain the matter dominance

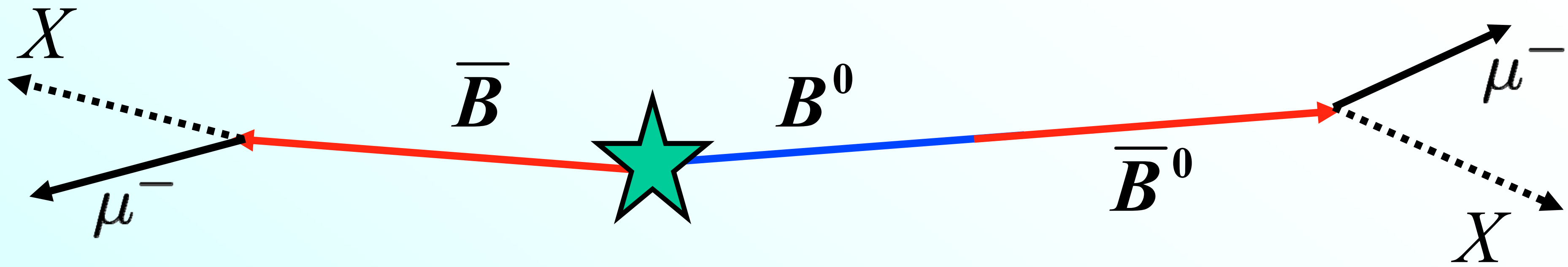
Search for new sources of *CP* violation –
an important task of current and future experiments

CP violation in mixing

- Main goal of our measurement is to study ***CP* violation in mixing** in the B_d and B_s systems
- Magnitude of this *CP* violation predicted by SM is negligible comparing to present experimental sensitivity
- Contribution of new physics can result in a significant modification of the SM prediction, which can be tested experimentally
  - Small SM value simplifies detection of possible deviation

A measurement of *CP* violation significantly different from zero would be unambiguous evidence of new physics

Dimuon charge asymmetry



- We measure *CP* violation in mixing using **the dimuon charge asymmetry of semileptonic *B* decays**:

$$\boxed{A_{sl}^{b} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}}$$

  - N_b^{++}, N_b^{--} – number of events with two b hadrons decaying semileptonically and producing two muons of the same charge
  - One muon comes from direct semileptonic decay $b \to \mu^- X$
  - Second muon comes from direct semileptonic decay after neutral B meson mixing: $B^0 \to \overline{B}^0 \to \mu^- X$

Dimuon and semileptonic charge asymmetry

- A^b_{sl} is equal to the charge asymmetry of "wrong sign" semileptonic B decays:

$$\boxed{a^b_{sl} \equiv \frac{\Gamma(\overline{B} \to \mu^+ X) - \Gamma(B \to \mu^- X)}{\Gamma(\overline{B} \to \mu^+ X) + \Gamma(B \to \mu^- X)} = A^b_{sl}}$$

  - See Y. Grossman, Y. Nir, G. Raz, PRL 97, 151801 (2006)
  - "Right sign" decay is $B \to \mu^+ X$
  - "Wrong sign" decays can happen only due to flavour oscillation in B_d and B_s
  - Semileptonic charge asymmetry can also be defined separately for B_d and B_s :

$$\boxed{a^q_{sl} \equiv \frac{\Gamma(\overline{B}^0_q \to \mu^+ X) - \Gamma(B^0_q \to \mu^- X)}{\Gamma(\overline{B}^0_q \to \mu^+ X) + \Gamma(B^0_q \to \mu^- X)}; \quad q = d, s}$$

$A^b{}_{\mathrm{sl}}$ at the Tevatron

- Since both B_d and B_s are produced at the Tevatron, $A^b{}_{\mathrm{sl}}$ is a linear combination of $a^d{}_{\mathrm{sl}}$ and $a^s{}_{\mathrm{sl}}$:
  - Need to know production fractions of B_d and B_s mesons at the Tevatron
  - Measured by the CDF experiment

$$\boxed{A_{sl}^b = (0.506 \pm 0.043) a_{sl}^d + (0.494 \pm 0.043) a_{sl}^s}$$

Unlike the experiments at *B* factories, the Tevatron gives a unique possibility to measure the charge asymmetry of both B_d and B_s

$A^b{}_{sl}$ and *CP* violation

- Non-zero value of $A^b{}_{sl}$ means that the semileptonic decays of B_q^0 and $\overline{B}_q^0$ are different
- It implies ***CP* violation in mixing**
  - it occurs only due to the mixing in the B_d and B_s systems
- It is quantitatively described by the CP violating phase ϕ_q of the $B^0{}_q$ ($q = d,s$) mass matrix:

$$\boxed{a_{sl}^q = \frac{\Delta\Gamma_q}{\Delta M_q} \tan(\phi_q)}$$

$A^b{}_{\mathrm{sl}}$ and the standard model

- Standard model predicts a very small value of $A^b{}_{\mathrm{sl}}$:

$$\boxed{A^b_{sl} = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}}$$

  - using prediction of $a^d{}_{\mathrm{sl}}$ and $a^s{}_{\mathrm{sl}}$ from A. Lenz, U. Nierste, hep-ph/0612167
  - New physics contribution can significantly change this value by changing the CP violating phases ϕ_d and ϕ_s

Our goal is to measure $A^b{}_{\mathrm{sl}}$ and compare it with the standard model prediction

Measurement Method

Experimental observables

- Experimentally, we measure two quantities:
- **Like-sign dimuon charge asymmetry**:

$$\boxed{A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}}$$

- **Inclusive muon charge asymmetry**:

$$\boxed{a \equiv \frac{n^{+} - n^{-}}{n^{+} + n^{-}}}$$

  - N^{++}, N^{--} – the number of events with two like-sign dimuons
  - n^{+}, n^{-} – the number of muons with given charge

Experimental observables and A^b_{sl}

- Semileptonic B decays contribute to both A and a;
- Both A and a linearly depend on the charge asymmetry A^b_{sl}

$$\boxed{\begin{aligned} a &= k\, A^b_{sl} + a_{bkg} \\ A &= K\, A^b_{sl} + A_{bkg} \end{aligned}}$$

  – recall that $A^b_{sl} = a^b_{sl}$

- In addition, there are detector related background contributions A_{bkg} and a_{bkg}

Our task is:

- Determine the background contributions A_{bkg} and a_{bkg}
- Find the coefficients K and k
- Extract the asymmetry A^b_{sl}

Background contribution

$$\boldsymbol{a = k\, A_{sl}^{b} + a_{bkg}}$$
$$\boldsymbol{A = K\, A_{sl}^{b} + A_{bkg}}$$

- Sources of background muons:
  - Kaon and pion decays $K^+ \to \mu^+ \nu$, $\pi^+ \to \mu^+ \nu$ or punch-through
  - proton punch-through
  - False track associated with muon track
  - Asymmetry of muon reconstruction

We measure all background contributions directly in data, with a reduced input from simulation

With this approach we expect to control and decrease the systematic uncertainties

Correlated background uncertainties

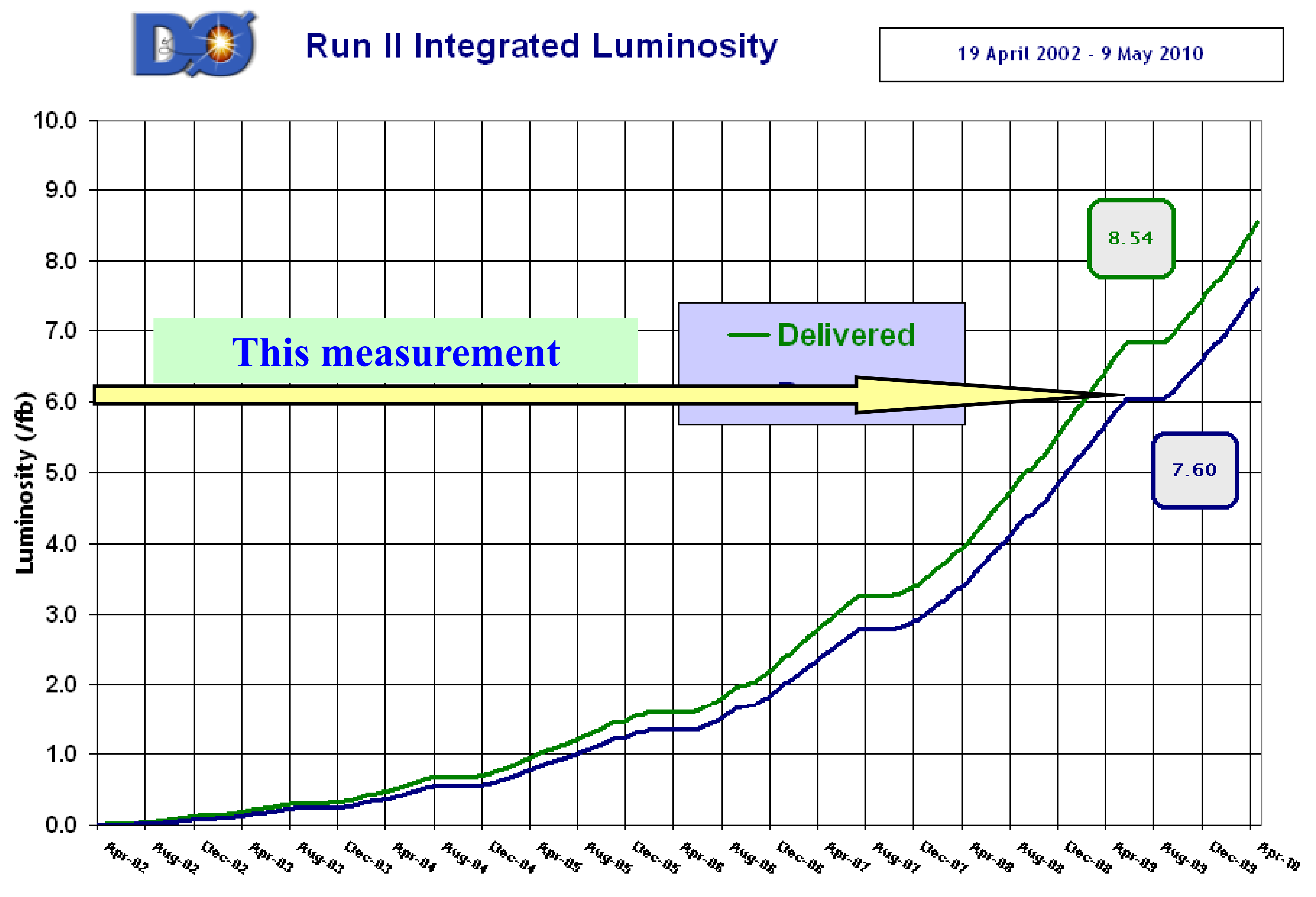
- The same background processes contribute to both A_{bkg} and a_{bkg}
- Therefore, the uncertainties of A_{bkg} and a_{bkg} are correlated
- We take advantage of the correlated background contributions, and obtain A^b_{sl} from the linear combination:

$$\boxed{A' \equiv A - \alpha a}$$

  - Coefficient α is selected such that the total uncertainty of A^b_{sl} is minimized

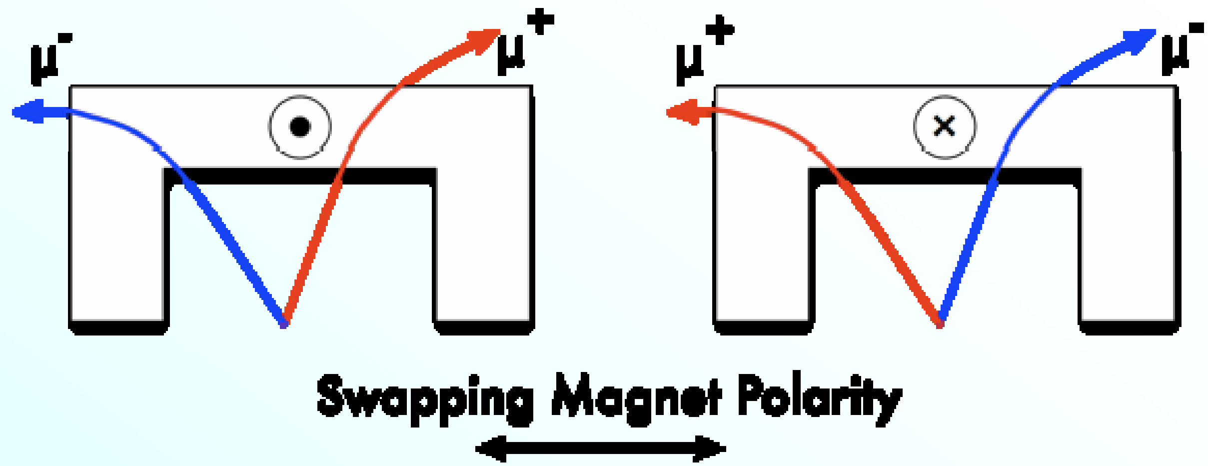
Measurement Details

Data in this analysis: 6.1 fb^{-1}



Reversal of Magnet Polarities

- Polarities of DØ solenoid and toroid are reversed regularly
- Trajectory of the negative particle becomes exactly the same as the trajectory of the positive particle with the reversed magnet polarity



- by analyzing 4 samples with different polarities (++, −−, +−, −+)
- the difference in the reconstruction efficiency between positive and negative particles is minimized

Changing polarities is an important feature of DØ detector, which reduces significantly systematics in charge asymmetry measurements

Event selection

- **Inclusive muon sample**:
  - Charged particle identified as a muon
  - $1.5 < p_T < 25$ GeV
  - muon with $p_T < 4.2$ GeV must have $|p_Z| > 6.4$ GeV
  - $|\eta| < 2.2$
  - Distance to primary vertex: <3 mm in axial plane; < 5 mm along the beam
- **Like-sign dimuon sample**:
  - Two muons of the same charge
  - Both muons satisfy all above conditions
  - Primary vertex is common for both muons
  - $M(\mu\mu) > 2.8$ GeV to suppress events with two muons from the same *B* decay

Blinded analysis

The central value of A^b_{sl} was extracted from the full data set only after the analysis method and all statistical and systematic uncertainties had been finalized

Raw asymmetries

$$a = k\ A_{sl}^{b} + a_{bkg}$$
$$A = K\ A_{sl}^{b} + A_{bkg}$$

- We select:
  - 1.495×10^{9} muon in the inclusive muon sample
  - 3.731×10^{6} events in the like-sign dimuon sample
- Raw asymmetries:

$$a \equiv \frac{n^{+} - n^{-}}{n^{+} + n^{-}}$$

$$a = (+0.955 \pm 0.003)\%$$
$$A = (+0.564 \pm 0.053)\%$$

$$A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

Detailed description of background

$$a = k\, A_{sl}^{b} + a_{bkg}$$
$$A = K\, A_{sl}^{b} + A_{bkg}$$

- Background contribution a_{bkg} to **inclusive muon sample**:

$$\boxed{a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta}$$

  - f_K, f_π, and f_p are the fractions of kaons, pions and protons identified as a muon in the inclusive muon sample
  - a_K, a_π, and a_p are the charge asymmetries of kaon, pion, and proton tracks
  - δ is the charge asymmetry of muon reconstruction
  - $f_{bkg} = f_K + f_\pi + f_p$

Detailed description of background

$$a = k\,A_{sl}^{b} + a_{bkg}$$
$$A = K\,A_{sl}^{b} + A_{bkg}$$

- Background contribution A_{bkg} to **like-sign dimuon sample**:

$$\boxed{A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta}$$

  - F_K, F_π, and F_p are the fractions of kaons, pions and protons identified as a muon in the like-sign dimuon sample
  - A_K, A_π, and A_p are the charge asymmetries of kaon, pion, and proton tracks
  - Δ is the charge asymmetry of muon reconstruction
  - $F_{bkg} = F_K + F_\pi + F_p$;

Kaon detection asymmetry

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

- The largest background asymmetry, and the largest background contribution comes from the charge asymmetry of kaon track identified as a muon (a_K, A_K)
- Interaction cross section of K^+ and K^- with the detector material is different, especially for kaons with low momentum
  - e.g., for $p(K) = 1$ GeV:

$$\sigma(K^- d) \approx 80\ \text{mb}$$
$$\sigma(K^+ d) \approx 33\ \text{mb}$$

- It happens because the reaction $K^- N \rightarrow Y\pi$ has no $K^+ N$ analogue

Kaon detection asymmetry

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

- K^+ meson travels further than K^- in the material, and has more chance of decaying to a muon
- It also has more chance to punch-through and produce a muon signal
- Therefore, the asymmetries a_K, A_K **should be positive**
- All other background asymmetries are found to be about ten times less

This asymmetry is difficult to model, and measuring it directly in data significantly reduces the related systematic uncertainties

Measurement of kaon asymmetry

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

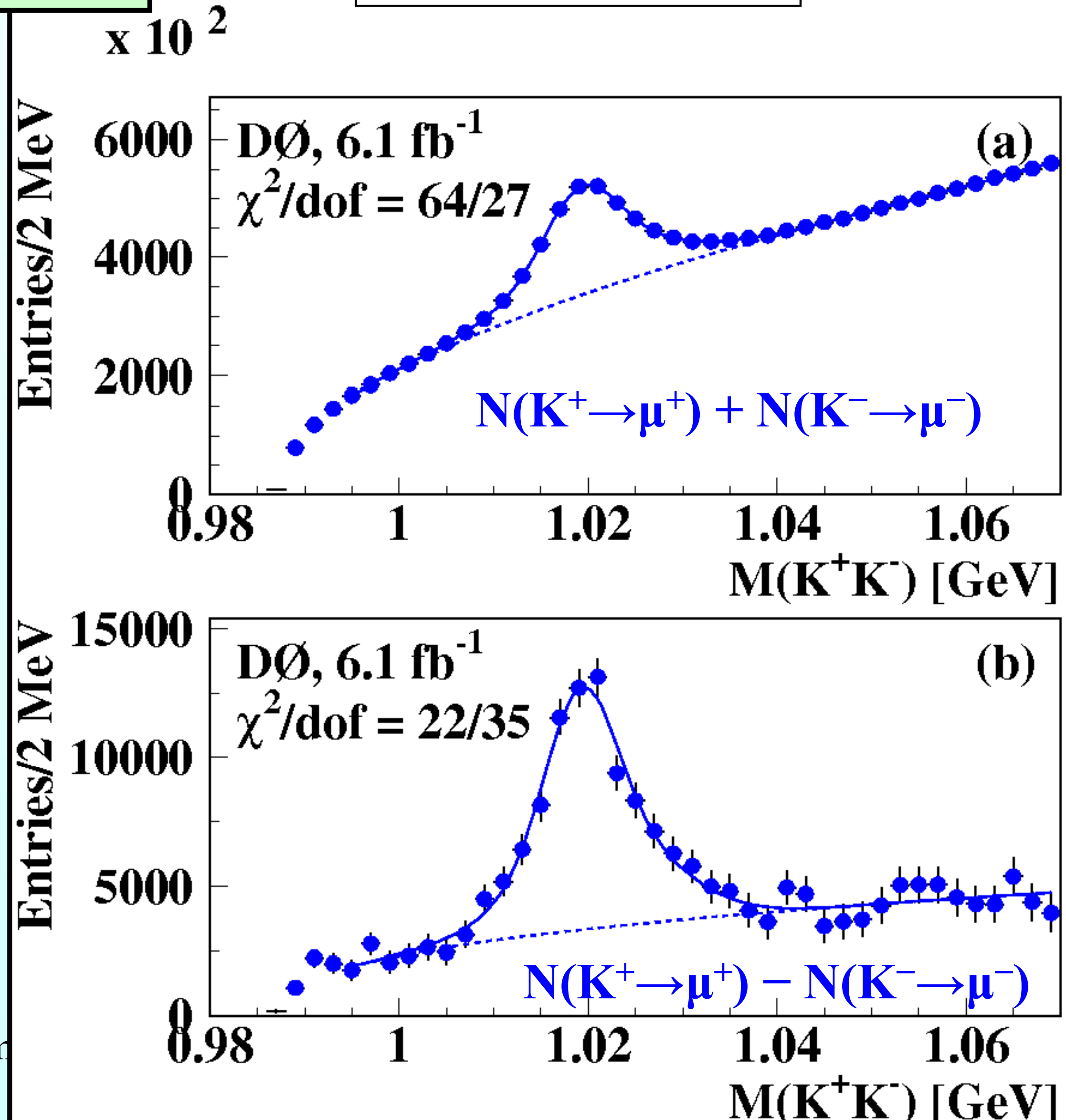
$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

- Define sources of kaons:

$$K^{*0} \to K^+\pi^-$$
$$\phi(1020) \to K^+K^-$$

- Require that the kaon is identified as a muon
- Build the mass distribution separately for positive and negative kaons
- Compute asymmetry in the number of observed events

$\phi \to K^+ K^-$ decay

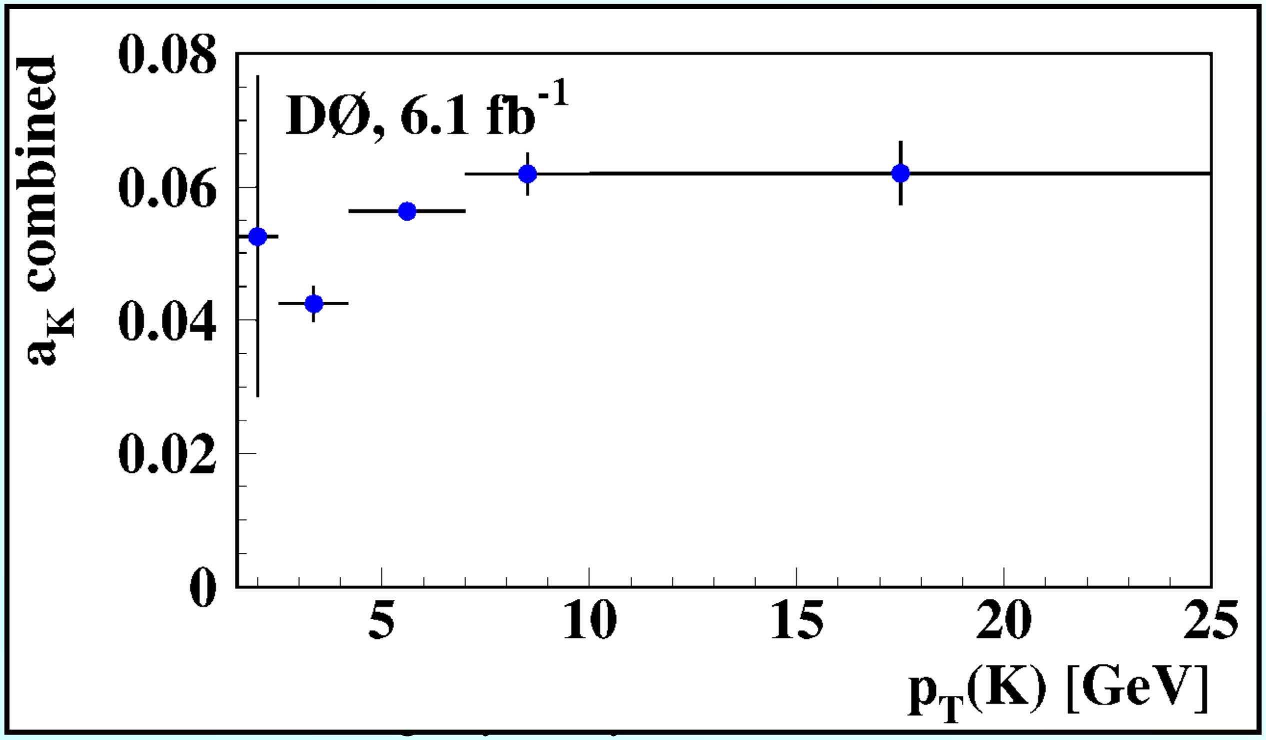


Measurement of kaon asymmetry

$$\boxed{a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta}$$

$$\boxed{A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta}$$

- Results from $K^{*0} \to K^+\pi^-$ and $\phi(1020) \to K^+K^-$ agree well
  - For the difference between two channels: $\chi^2/\mathrm{dof} = 5.4 / 5$
- We combine the two channels together:



Measurement of a_π, a_p

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

- The asymmetries a_π , a_p are measured using the decays $K_S \to \pi^+ \pi^-$ and $\Lambda \to p\,\pi^-$ respectively
- Similar measurement technique is used

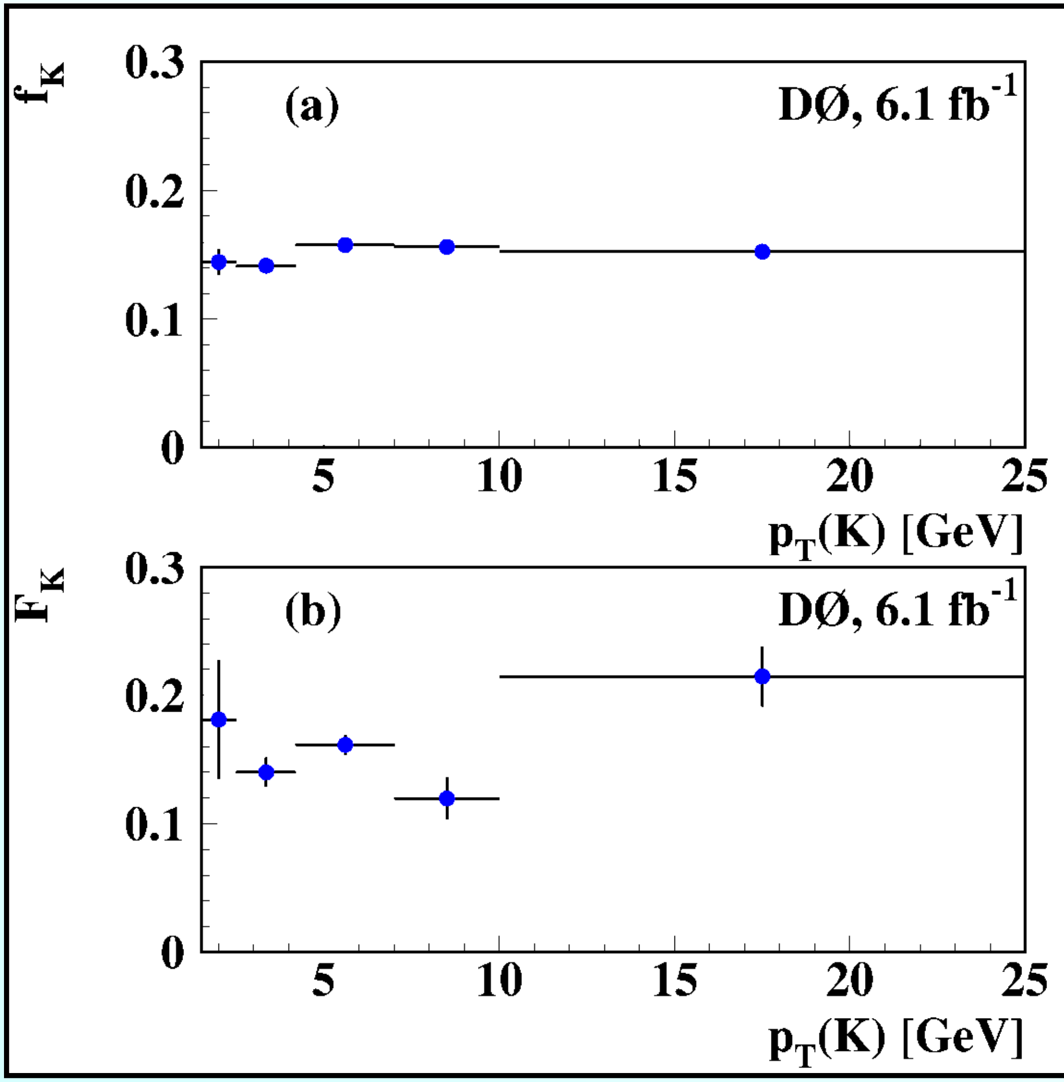
	a_K	a_π	a_p
Data	$(+5.51 \pm 0.11)\%$	$+(0.25 \pm 0.10)\%$	$(+2.3 \pm 2.8)\%$

Measurement of f_K, F_K

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

- Fractions f_K , F_K are measured using the decays $K^{*0} \to K^+\pi^-$
- We measure $f_{K^{*0}}$, $F_{K^{*0}}$
- We find $f_{K^{*0}}/f_K$ using the similar decay $K^{*+} \to K_S\pi^-$
  - In this decay we measure $f_{K^{*+}}/f_{Ks}$ and convert it into $f_{K^{*0}}/f_K$

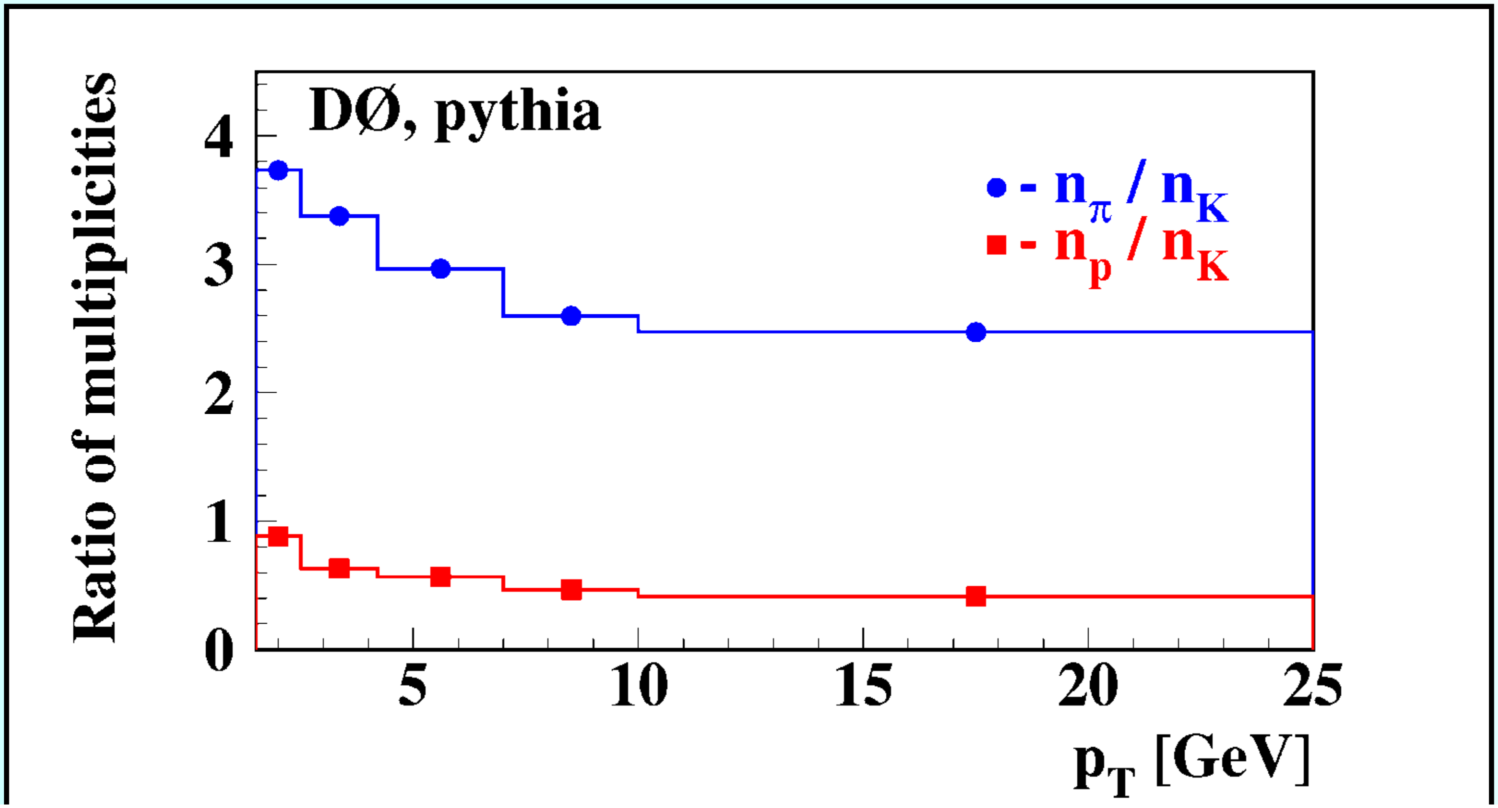


Measurement of f_π , f_p , F_π , F_p

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

- Fractions f_π , f_p, F_π , F_p are obtained using f_K , F_K with an additional input from simulation on the ratio of multiplicities n_π / n_K and n_p / n_K



Summary of background composition

$$\boxed{f_{bkg} = f_k + f_\pi + f_p}$$

- We get the following background fractions in the inclusive muon events:

	$(1-f_{bkg})$	f_K	f_π	f_p
MC	(59.0±0.3)%	(14.5±0.2)%	(25.7±0.3)%	(0.8±0.1)%
Data	(58.1±1.4)%	(15.5±0.2)%	(25.9±1.4)%	(0.7±0.2)%

  - Uncertainties for both data and simulation are statistical
  - Simulation fractions are given as a cross-check only, and **are not used in the analysis**
  - Good agreement between data and simulation within the systematic uncertainties assigned

Muon reconstruction asymmetry

$$\boxed{a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta}$$

$$\boxed{A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta}$$

- Reversal of toroid and solenoid polarities cancel the first-order detector effects
- Quadratic terms in detector asymmetries still can contribute into the muon reconstruction asymmetry
- Detector asymmetries for a given magnet polarity $a_{det} \approx O(1\%)$
- We can expect the residual reconstruction asymmetry :

$$\delta \approx \Delta \approx O(0.01\%)$$

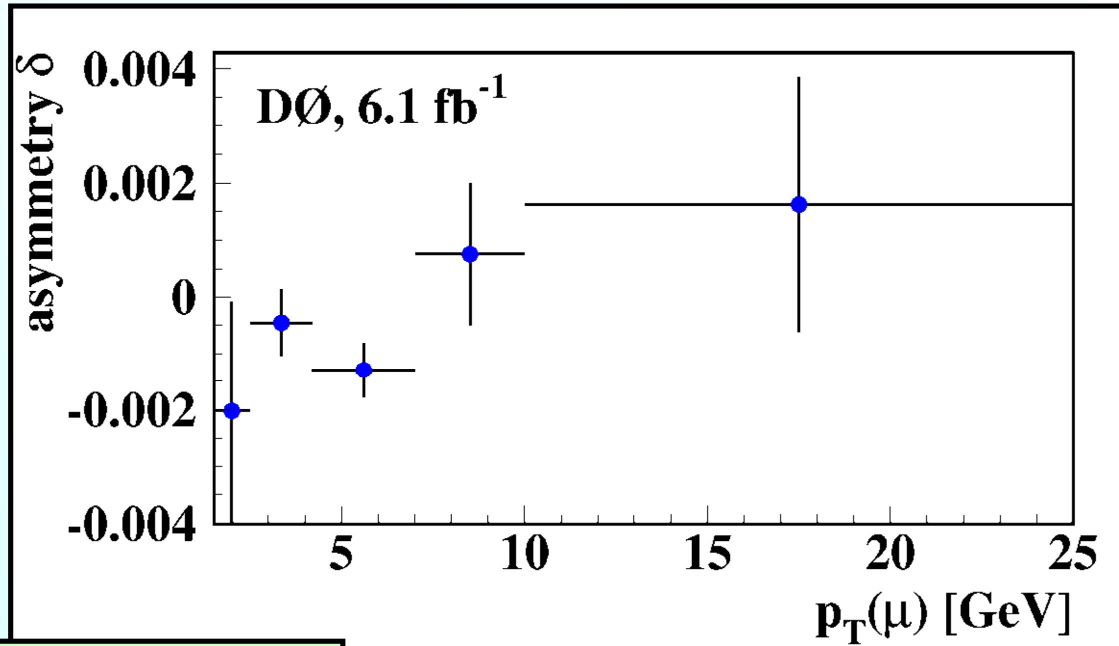
Muon reconstruction asymmetry

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

- We measure the muon reconstruction asymmetry using $J/\psi \to \mu\mu$ events
- Average asymmetries δ and Δ are:

$$\delta = (-0.076 \pm 0.028)\%$$
$$\Delta = (-0.068 \pm 0.023)\%$$



- To be compared with:

$$a = (+0.955 \pm 0.003)\%$$
$$A = (+0.564 \pm 0.053)\%$$

Such small values of reconstruction asymmetries are a direct consequence of the regular reversal of magnet polarities during data taking

Summary of background contribution

$$\boxed{a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta}$$

$$\boxed{A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta}$$

- We obtain:

	$f_K a_K$ (%) or $F_K A_K$ (%)	$f_\pi a_\pi$ (%) or $F_\pi A_\pi$ (%)	$f_p a_p$ (%) or $F_p A_p$ (%)	$(1-f_{bkg})\delta$ (%) or $(2-F_{bkg})\Delta$ (%)	a_{bkg} or A_{bkg}
Inclusive	0.854±0.018	0.095±0.027	0.012±0.022	−0.044±0.016	0.917±0.045
Dimuon	0.828±0.035	0.095±0.025	0.000±0.021	−0.108±0.037	0.815±0.070

- All uncertainties are statistical
- Notice that background contribution is similar for inclusive muon and dimuon sample: $A_{bkg} \approx a_{bkg}$

Signal contribution

$$k\,A^b_{sl} = a - a_{bkg}$$
$$K\,A^b_{sl} = A - A_{bkg}$$

$$a \equiv \frac{n^+ - n^-}{n^+ + n^-}$$

$$A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

- After subtracting the background contribution from the "raw" asymmetries *a* and *A*, the remaining residual asymmetries are proportional to $A^b{}_{\mathrm{sl}}$
- In addition to the oscillation process $\bar{B}^0_q \to B^0_q \to \mu^+ X$, several other decays of b- and c-quark contribute to inclusive muon and like-sign dimuon sample
- All processes except $\bar{B}^0_q \to B^0_q \to \mu^+ X$ don't produce any charge asymmetry, but rather dilute the values of *a* and *A* by contributing in the denominator of these asymmetries

Coefficients *k* and *K*

$$\boxed{\begin{aligned} k\, A_{sl}^{b} &= a - a_{bkg} \\ K\, A_{sl}^{b} &= A - A_{bkg} \end{aligned}}$$

- Coefficients *k* and *K* take into account this dilution of "raw" asymmetries *a* and *A*
- They are determined using the simulation of *b*- and *c*-quark decays
  - These decays are currently measured with a good precision, and this input from simulation produces a small systematic uncertainty
- Coefficient *k* is found to be much smaller than *K*, because many more non-oscillating *b*- and *c*-quark decays contribute to the asymmetry *a*:

$$\boxed{\begin{aligned} k &= 0.041 \pm 0.003 \\ K &= 0.342 \pm 0.023 \end{aligned}}$$

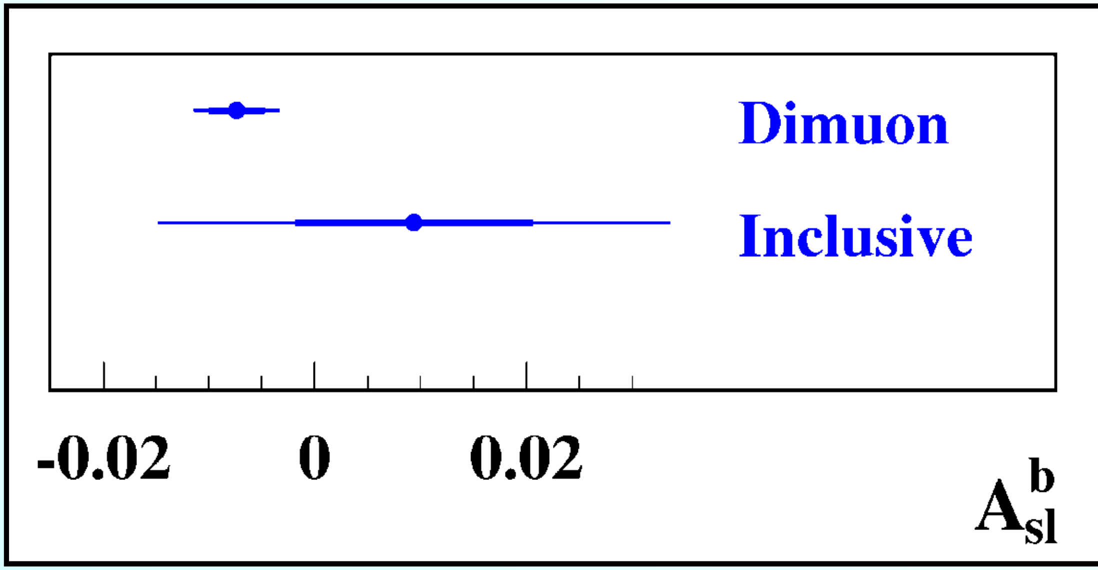
$$\boxed{\frac{k}{K} = 0.12 \pm 0.01}$$

Bringing everything together

- Using all results on background and signal contribution we get two separate measurements of $A^b{}_{sl}$ from inclusive and like-sign dimuon samples:

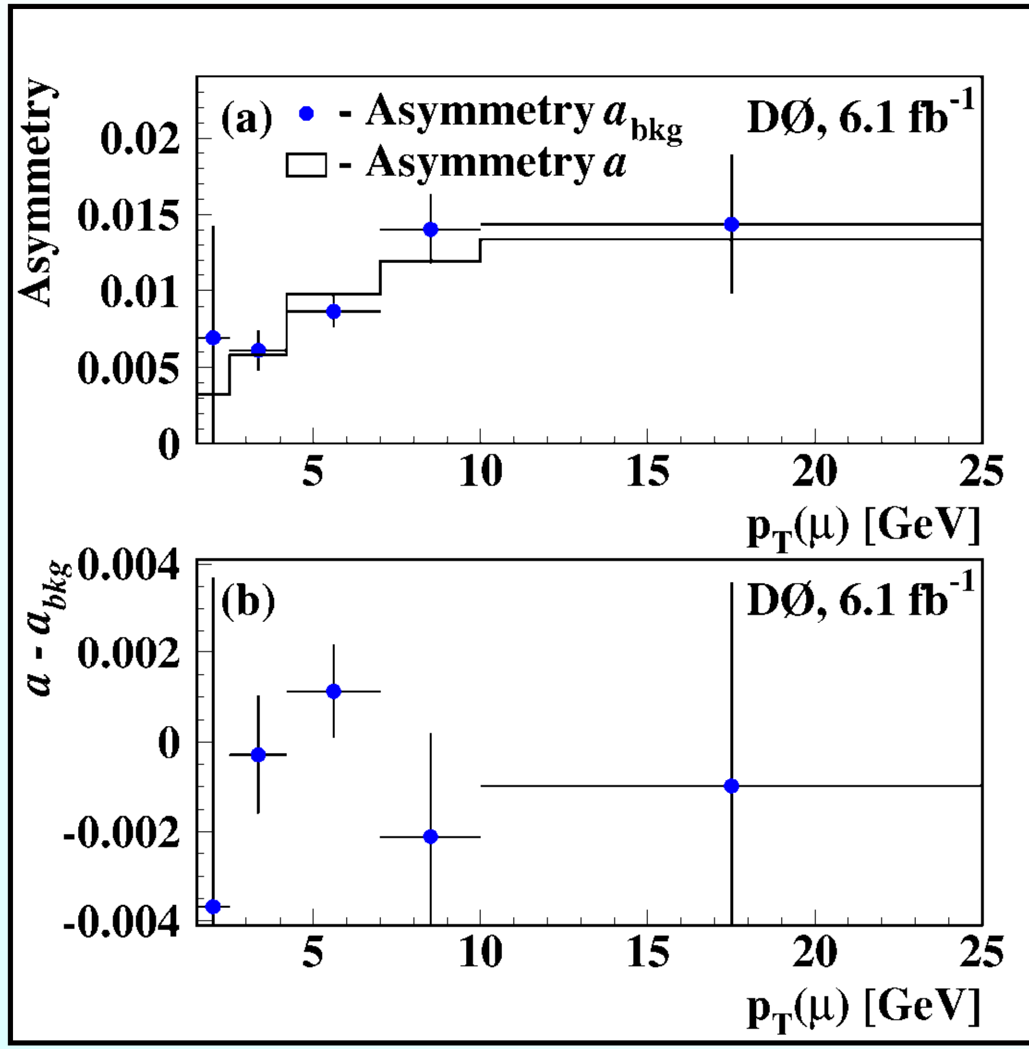
$$A^b_{sl} = (+0.94 \pm 1.12\,(\text{stat}) \pm 2.14\,(\text{syst}))\% \quad \text{(from inclusive)}$$
$$A^b_{sl} = (-0.736 \pm 0.266\,(\text{stat}) \pm 0.305\,(\text{syst}))\% \quad \text{(from dimuon)}$$

  - Uncertainties of the first result are much larger, because of a small coefficient $k = 0.041 \pm 0.003$
  - Dominant contribution into the systematic uncertainty comes from the measurement of f_K and F_K fractions



Closure test

- The contribution of A^b_{sl} in the inclusive muon asymmetry a is suppressed by $k = 0.041 \pm 0.003$
- The value of a is mainly determined by the background asymmetry a_{bkg}
- We measure a_{bkg} in data, and we can verify how well does it describe the observed asymmetry a
- We compare a and a_{bkg} as a function of muon p_T
- We get $\chi^2/\text{dof} = 2.4/5$ for the difference between these two distributions



Excellent agreement between the expected and observed values of a, including a p_T dependence

Combination of measurements

- Many uncertainties in these two measurements are correlated
- Obtain the final result using the linear combination:

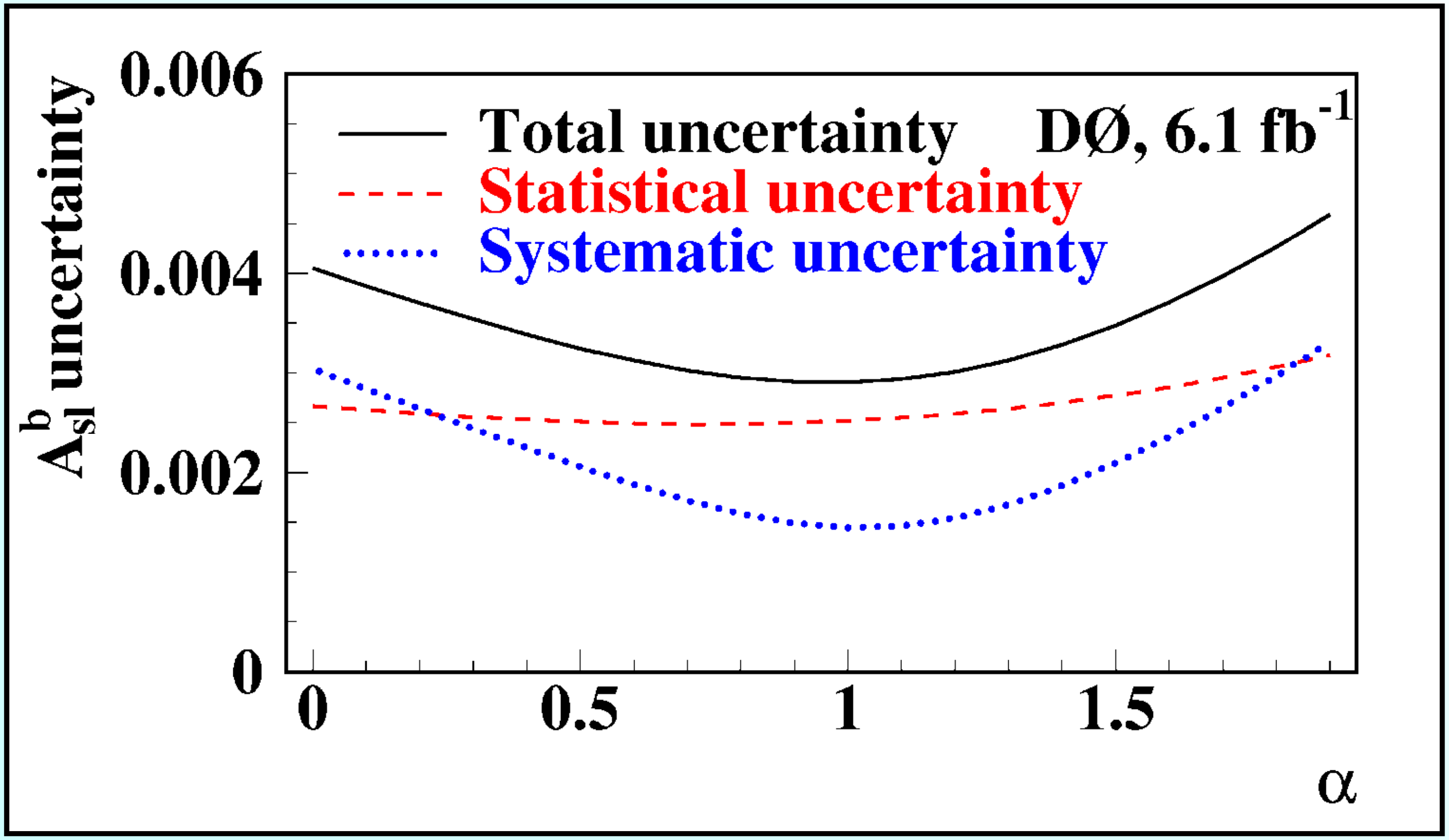
$$\boxed{A' \equiv A - \alpha a = (K - \alpha k) A_{sl}^{b} + (A_{bkg} - \alpha a_{bkg})}$$

  – The parameter α is selected such that the total uncertainty of A^b_{sl} is minimized

- Since $A_{bkg} \approx a_{bkg}$ and the uncertainties of these quantities are correlated, we can expect the cancellation of background uncertainties in A' for $\alpha \approx 1$
- The signal asymmetry A^b_{sl} does not cancel in A' for $\alpha \approx 1$ because: $\boxed{k << K}$

Combination of measurements

- Optimal value of α is obtained by the scan of the total uncertainty of A^b_{sl} obtained from A'
- • The value α=0.959 is selected:



Final result

Final result

- From $A' = A - \alpha a$ we obtain a value of A^b_{sl} :

$$\boxed{A^b_{sl} = (-0.957 \pm 0.251\,(\text{stat}) \pm 0.146\,(\text{syst}))\%}$$

- To be compared with the SM prediction:

$$\boxed{A^b_{sl}(SM) = (-0.023^{+0.005}_{-0.006})\%}$$

- This result differs from the SM prediction by ~3.2 σ

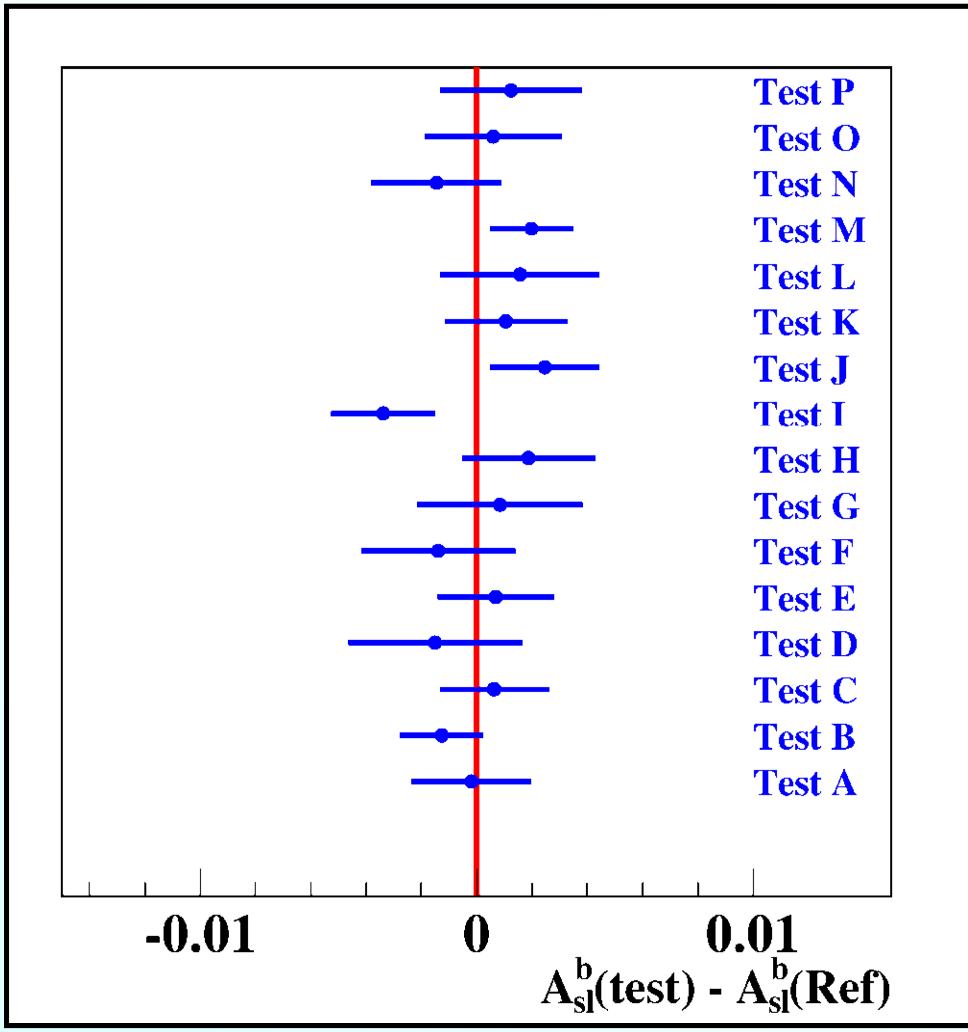
Statistical and systematic uncertainties

Source	A^b_{sl} inclusive muon	A^b_{sl} dimuon	A^b_{sl} combined
A or a (stat)	0.00066	0.00159	0.00179
f_K or F_K (stat)	0.00222	0.00123	0.00140
$P(\pi \to \mu)/P(K \to \mu)$	0.00234	0.00038	0.00010
$P(p \to \mu)/P(K \to \mu)$	0.00301	0.00044	0.00011
A_K	0.00410	0.00076	0.00061
A_π	0.00699	0.00086	0.00035
A_p	0.00478	0.00054	0.00001
δ or Δ	0.00405	0.00105	0.00077
f_K or F_K (syst)	0.02137	0.00300	0.00128
π, K, p multiplicity	0.00098	0.00025	0.00018
c_b or C_b	0.00080	0.00046	0.00068
Total statistical	0.01118	0.00266	0.00251
Total systematic	0.02140	0.00305	0.00146
Total	0.02415	0.00405	0.00290

Dominant uncertainties

Consistency tests

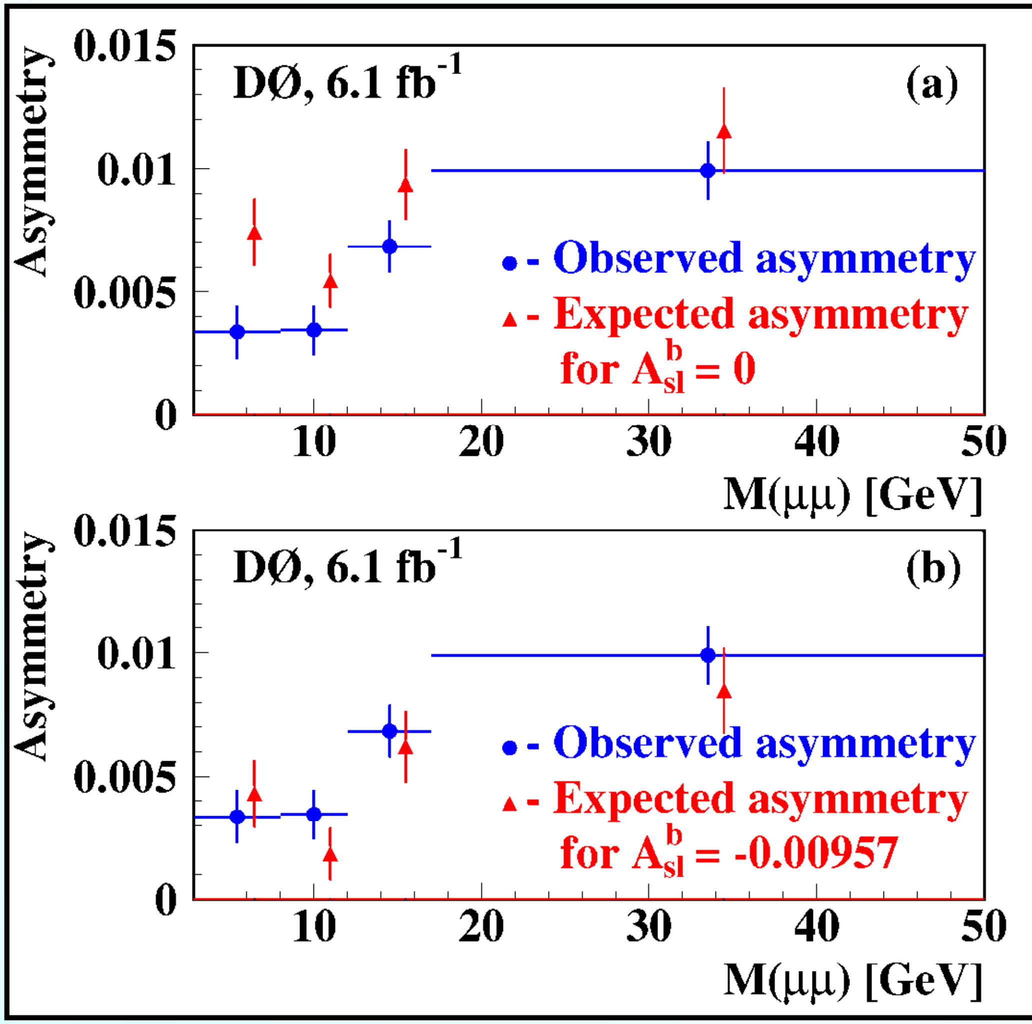
- We modify selection criteria, or use a part of sample to test the stability of result
- 16 tests in total are performed
- Very big variation of raw asymmetry A (up to 140%) due to variation of background, but A^b_{sl} remains stable



Developed method is stable and gives consistent result after modifying selection criteria in a wide range

Dependence on dimuon mass

- We compare the expected and observed dimuon charge asymmetry for different masses of $\mu\mu$ pair
- The expected and observed asymmetries agree well for $A^b_{sl} = -0.00957$
- No singularity in the $M(\mu\mu)$ shape supports B physics as the source of anomalous asymmetry



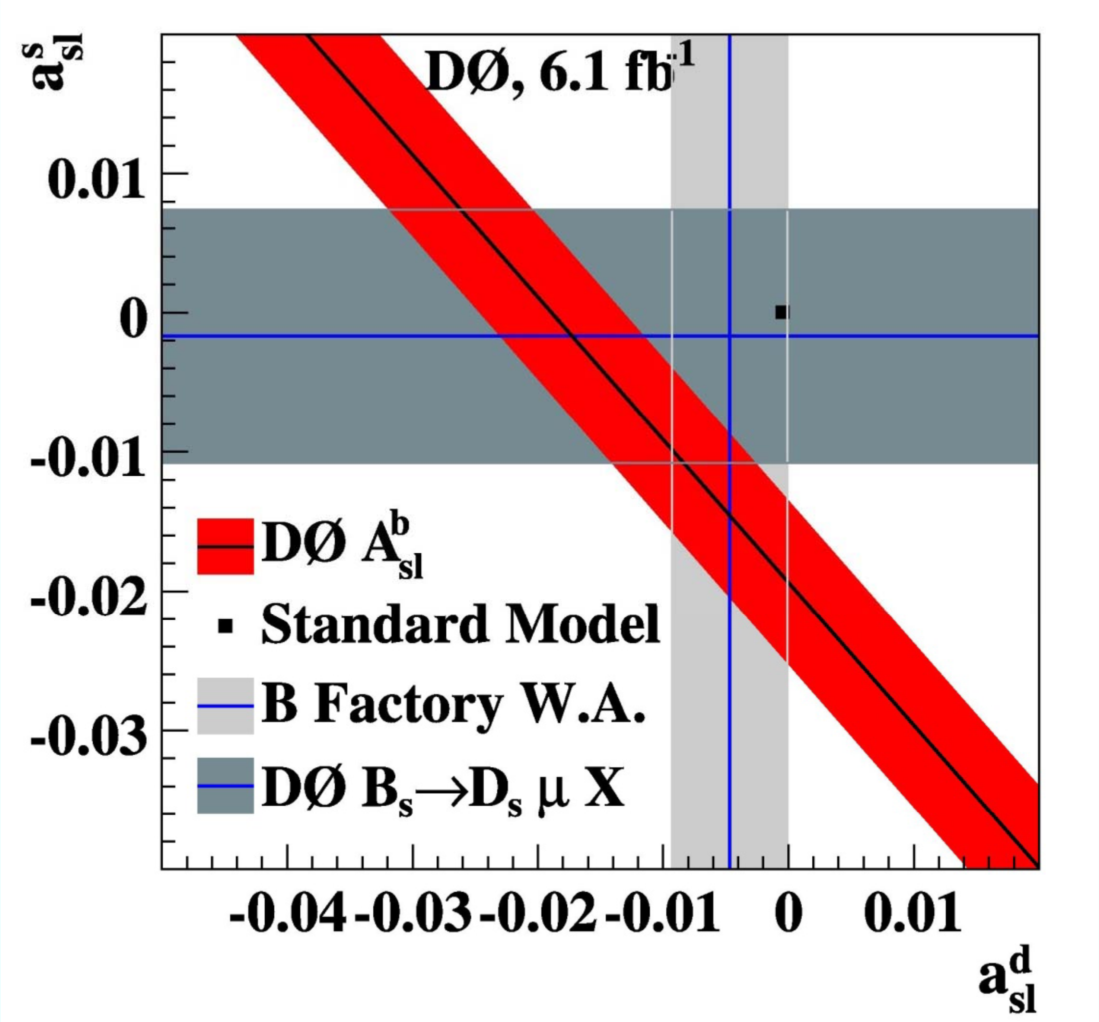
Dependence on the dimuon mass is well described by the analysis method

Comparison with other measurements

- In this analysis we measure a linear combination of a^d_{sl} and a^s_{sl}:

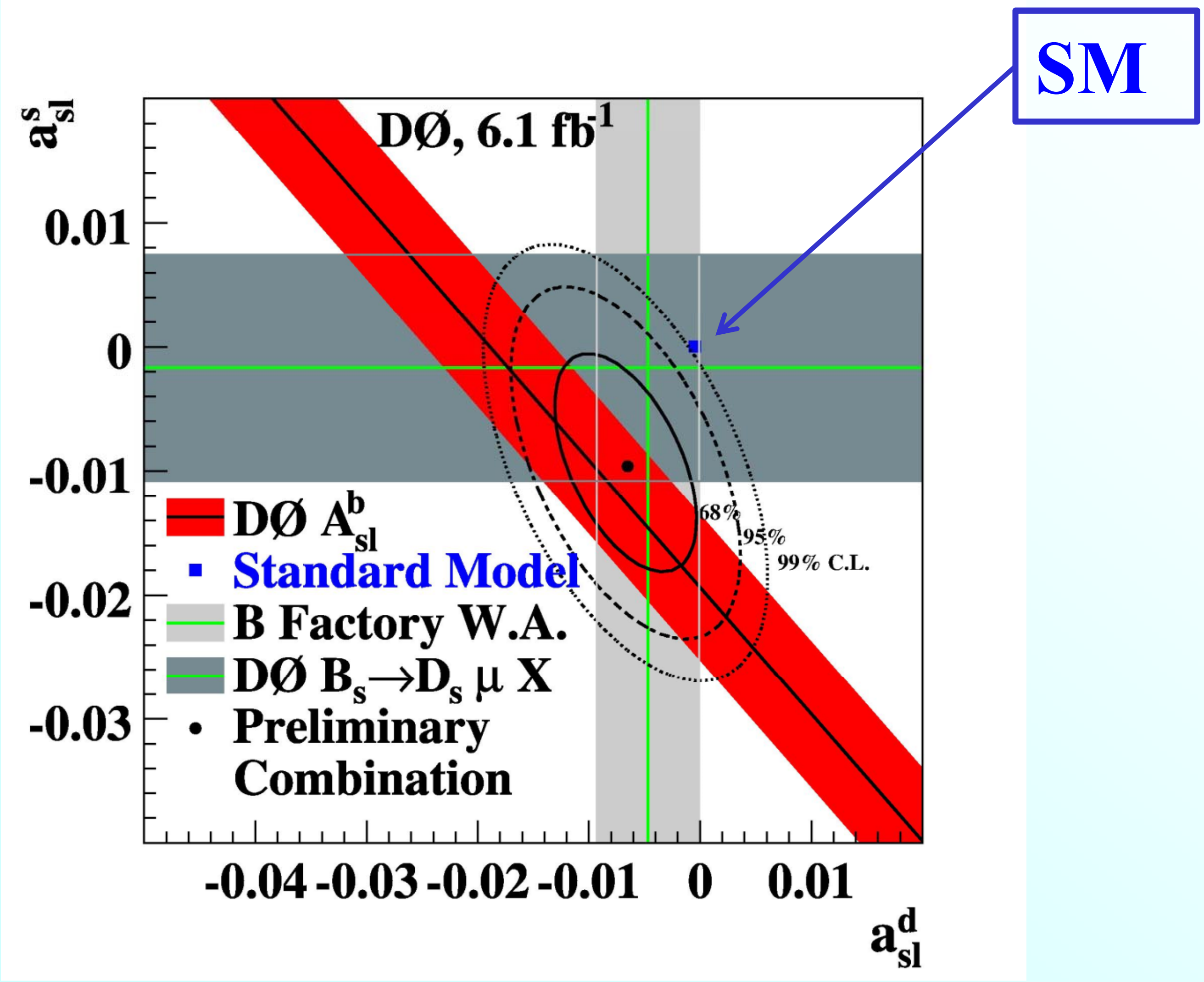
$$\boxed{A^b_{sl} = 0.506\, a^d_{sl} + 0.494\, a^s_{sl}}$$

- Obtained result agrees well with other measurements of a^d_{sl} and a^s_{sl}



preliminary combination

- Our (preliminary) combination of all measurements of semileptonic charge asymmetry shows a similar deviation from the SM.



Value of a^s_{sl}

- Obtained A^b_{sl} value can be translated to the semileptonic charge asymmetry of B_s meson
- We need additional input of $a^d_{\mathrm{sl}} = -0.0047 \pm 0.0046$ measured at B factories
- We obtain:

$$\boxed{a^s_{sl} = (-1.46 \pm 0.75)\%}$$

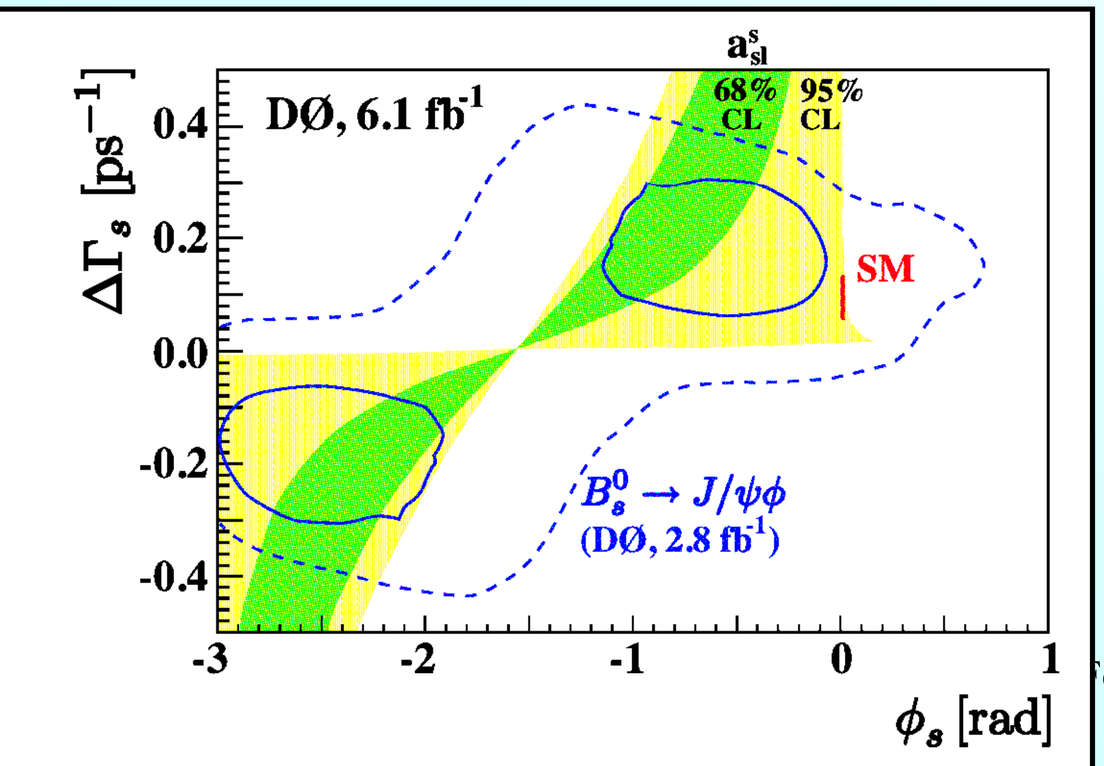
- To be compared with the SM prediction:

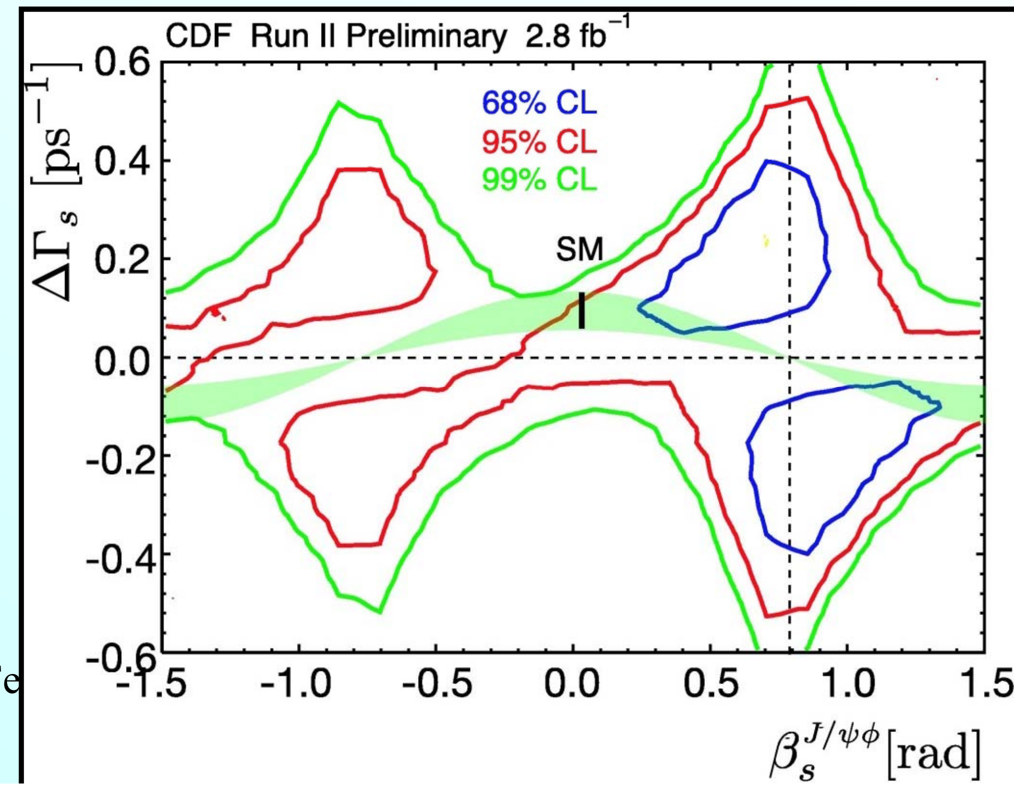
$$\boxed{a^b_{sl}(SM) = (+0.0021 \pm 0.0006)\%}$$

- Disagreement with the SM is reduced because of additional experimental input of a^d_{sl}

Comparison with other measurements

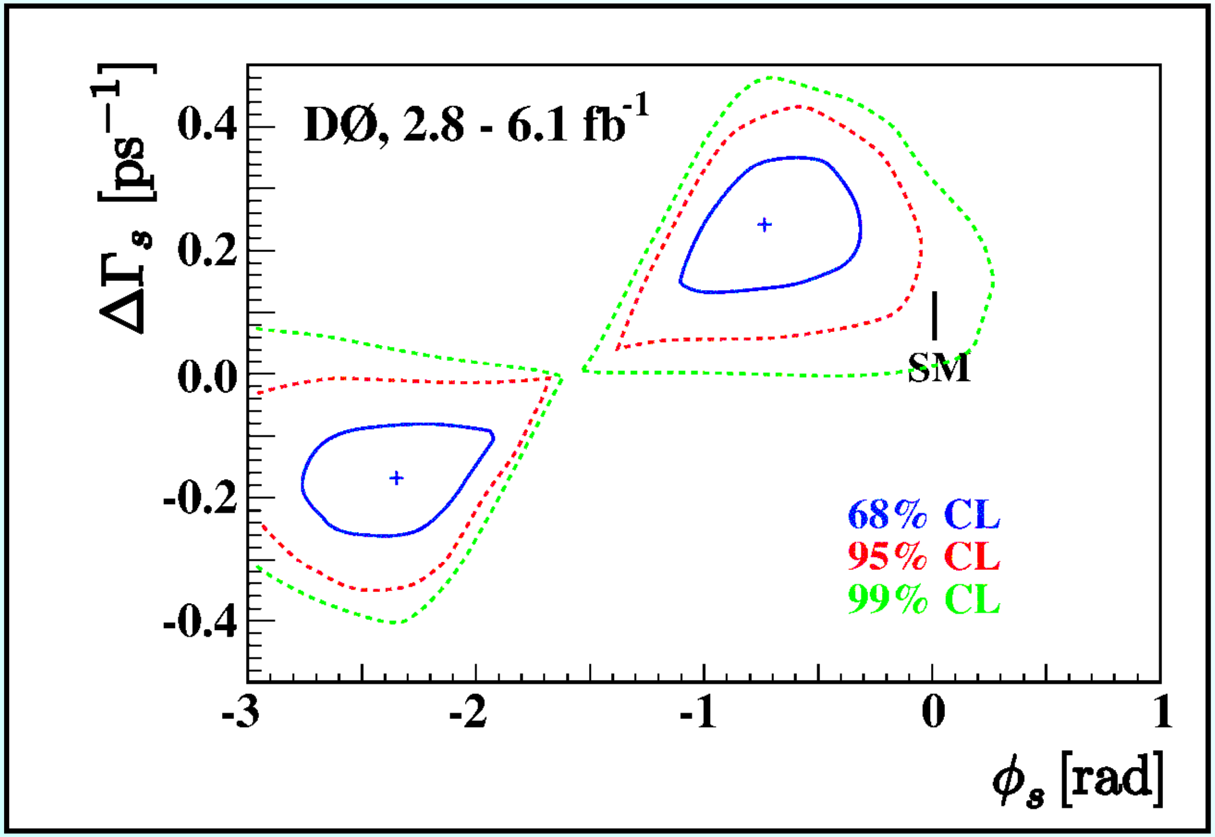
- Obtained value of a^s_{sl} can be translated into the measurement of the CP violating phase ϕ_s and $\Delta\Gamma_s$
- This constraint is in excellent agreement with an independent measurement of ϕ_s and $\Delta\Gamma_s$ in $B_s \to J/\psi\phi$ decay
- This result is also consistent with the CDF measurement in this channel





Combination of results

- This measurement and the result of DØ analysis in $B_s \to J/\psi\phi$ can be combined together
- This combination excludes the SM value of ϕ_s at more than 95% C.L.



This result at a glance

- Evidence of an anomalous charge asymmetry in the number of muons produced in the initially *CP* symmetric $p\bar{p}$ interaction
- This asymmetry is not consistent with the SM prediction at a 3.2σ level
- This new result is consistent with other measurements
- We observe that the number of produced particles of matter (negative muons) is larger than the number of produced particles of antimatter
- Therefore, the sign of observed asymmetry is consistent with the sign of *CP* violation required to explain the abundance of matter in our Universe

This result may provide an important input for explaining the matter dominance in our Universe

Conclusions

- New measurement of $A^b{}_{sl}$ is performed

$$\boxed{A_{sl}^{b} = (-0.957 \pm 0.251\,(\text{stat}) \pm 0.146\,(\text{syst})\,)\%}$$

- Almost all relevant quantities are obtained from data with minimal input from simulation
- Closure test shows good agreement between expected and observed asymmetries in the inclusive muon sample;
- Result differs from the SM prediction by 3.2σ
- Result is consistent with other measurements of CP violation in mixing
- Dominant uncertainty is statistical – precision can be improved with more luminosity

Backup slides

$A^b_{\rm sl}$ and *CP* violation

- Non-zero value of $A^b_{\rm sl}$ means that the semileptonic decays of B^0_q and $\overline{B}^0_q$ are different;
- It implies *CP* violation in mixing;
  - it occurs only due to the mixing in B_d and B_s ;
- Quantity describing *CP* violation in mixing is the complex phase ϕ_q of the B^0_q ($q = d,s$) mass matrix:

$$\|\mathbf{M}_q\| = \begin{bmatrix} M_q & M_q^{12} \\ (M_q^{12})^* & M_q \end{bmatrix} - \frac{i}{2}\begin{bmatrix} \Gamma_q & \Gamma_q^{12} \\ (\Gamma_q^{12})^* & \Gamma_q \end{bmatrix}$$

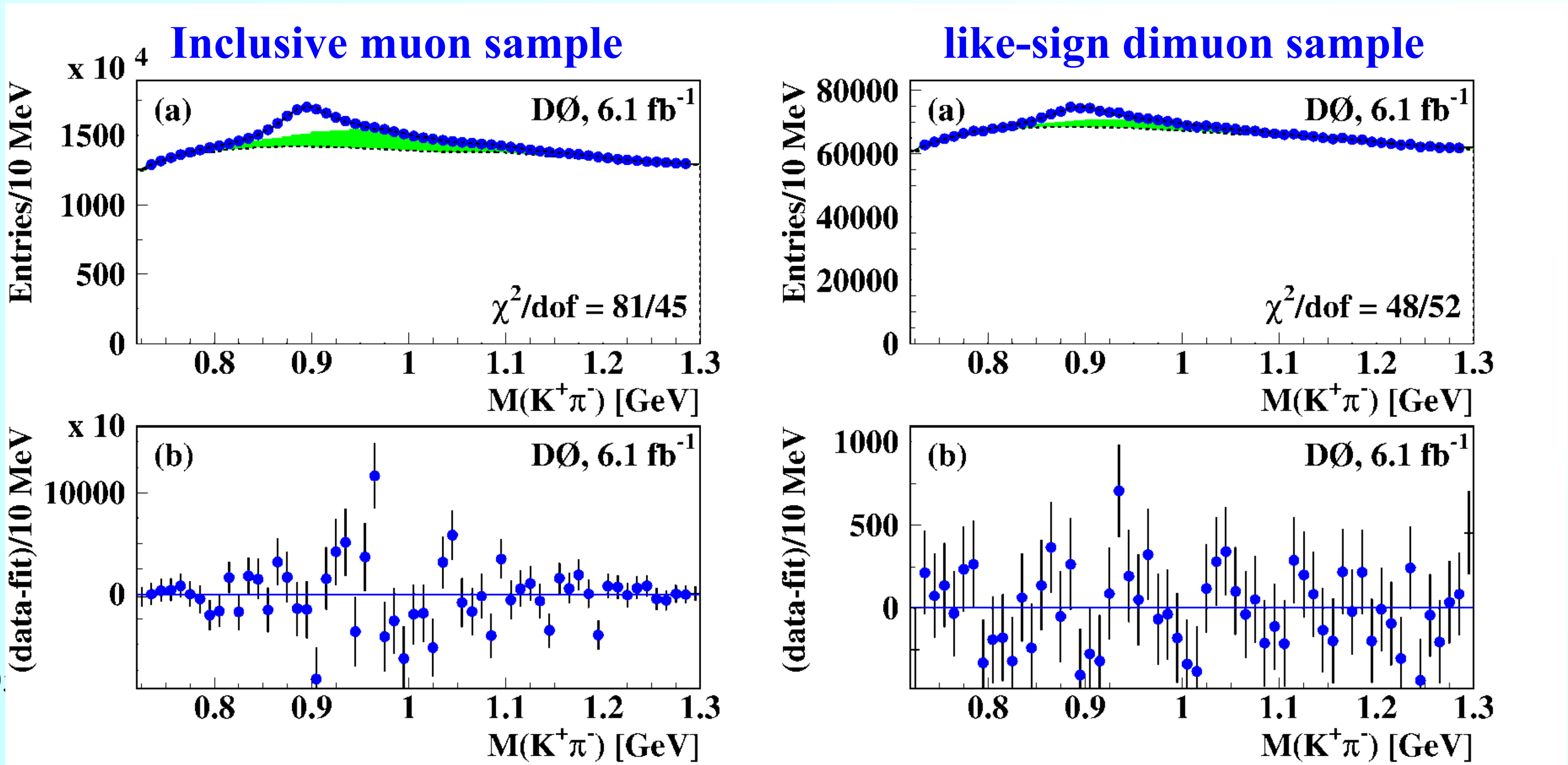
$$\begin{aligned} \Delta M_q &= M_H - M_L \approx 2\left|M_q^{12}\right| \\ \Delta\Gamma_q &= \Gamma_L - \Gamma_H \approx 2\left|\Gamma_q^{12}\right|\cos\phi_q \\ \phi_q &= \arg\left(-\frac{M_q^{12}}{\Gamma_q^{12}}\right) \end{aligned}$$

- $a^q_{\rm sl}$ is related with the CP violating phase ϕ_q as:

$$a^q_{sl} = \frac{\Delta\Gamma_q}{\Delta M_q}\tan(\phi_q)$$

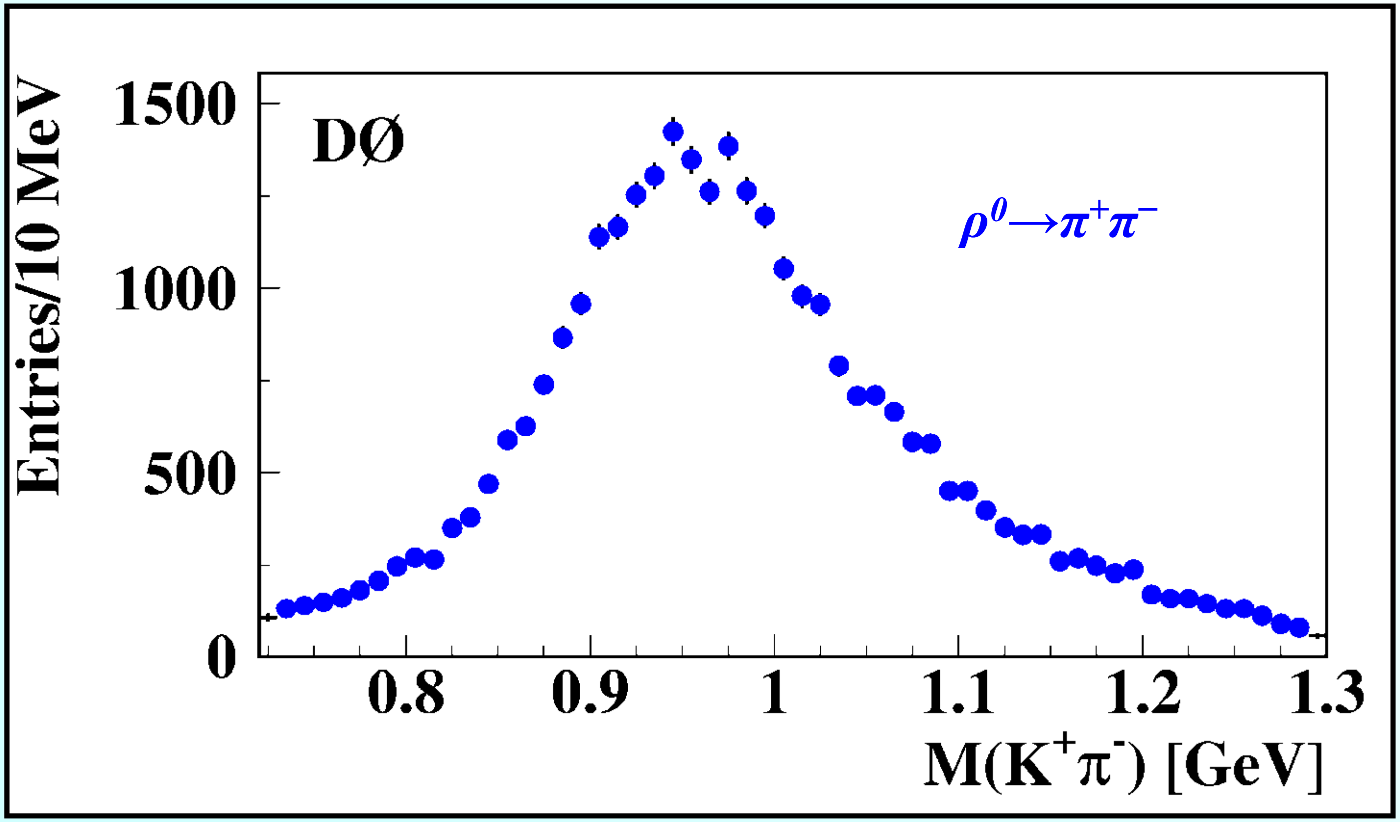
Measurement of f_K, F_K

- Fractions f_K , F_K are measured using the decays $K^{*0} \to K^+\pi^-$ selected in the inclusive muon and like-sign dimuon samples respectively;
- Kaon is required to be identified as a muon;
- We measure fractions $f_{K^{*0}}$, $F_{K^{*0}}$;



Peaking background contribution

- Decay $\rho^0 \to \pi^+\pi^-$ produces a peaking background in the (Kπ) mass
- The mass distribution from $\rho^0 \to \pi^+\pi^-$ is taken from simulation



Measurement of f_K, F_K

- To convert these fractions to f_K , F_K we need to know the fraction $R(K^{*0})$ of charged kaons from $K^{*0} \to K^+\pi^-$ and the efficiency to reconstruct an additional pion ε_0 :

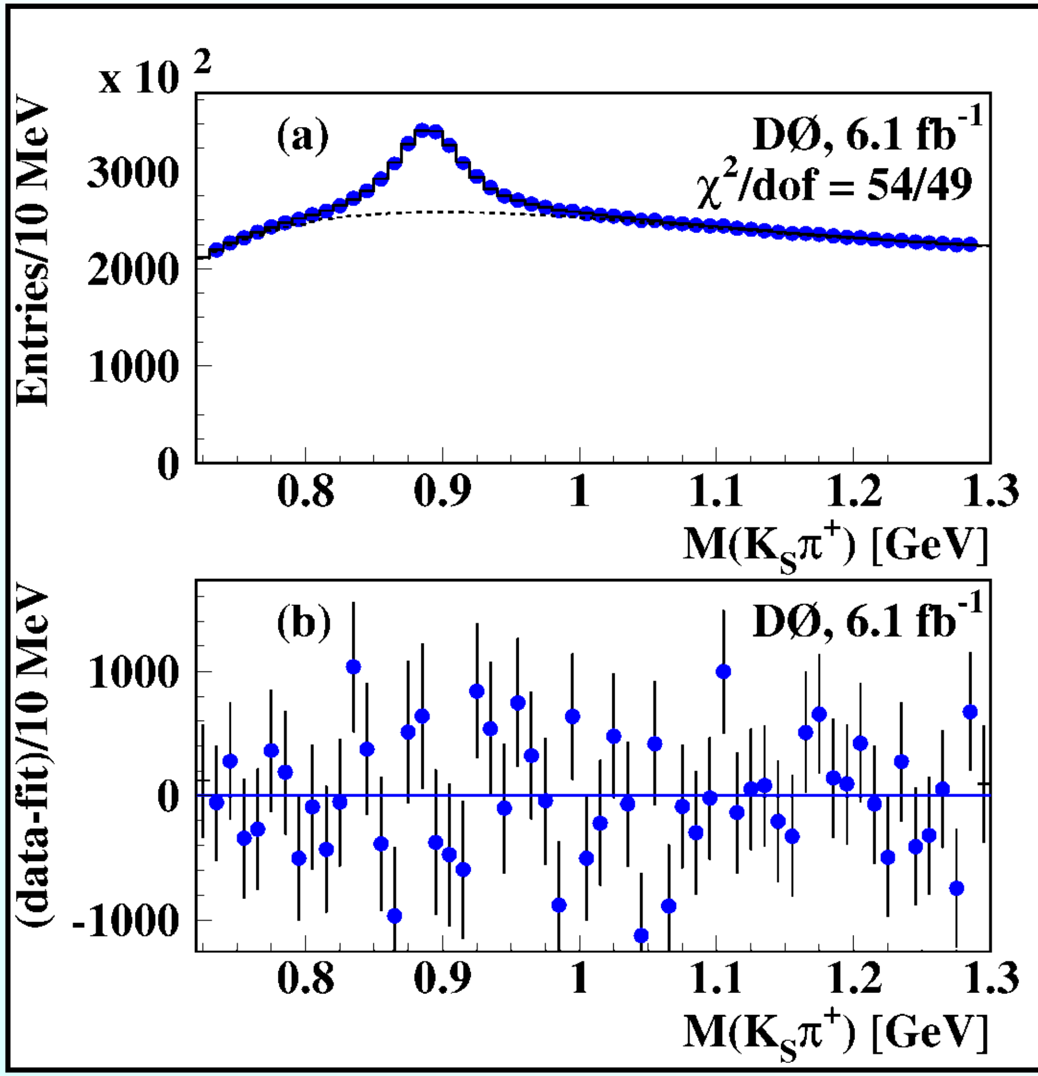
$$\boxed{f_{K^*0} = f_K R(K^{*0})\varepsilon_0; \quad F_{K^*0} = F_K R(K^{*0})\varepsilon_0}$$

Measurement of f_K, F_K

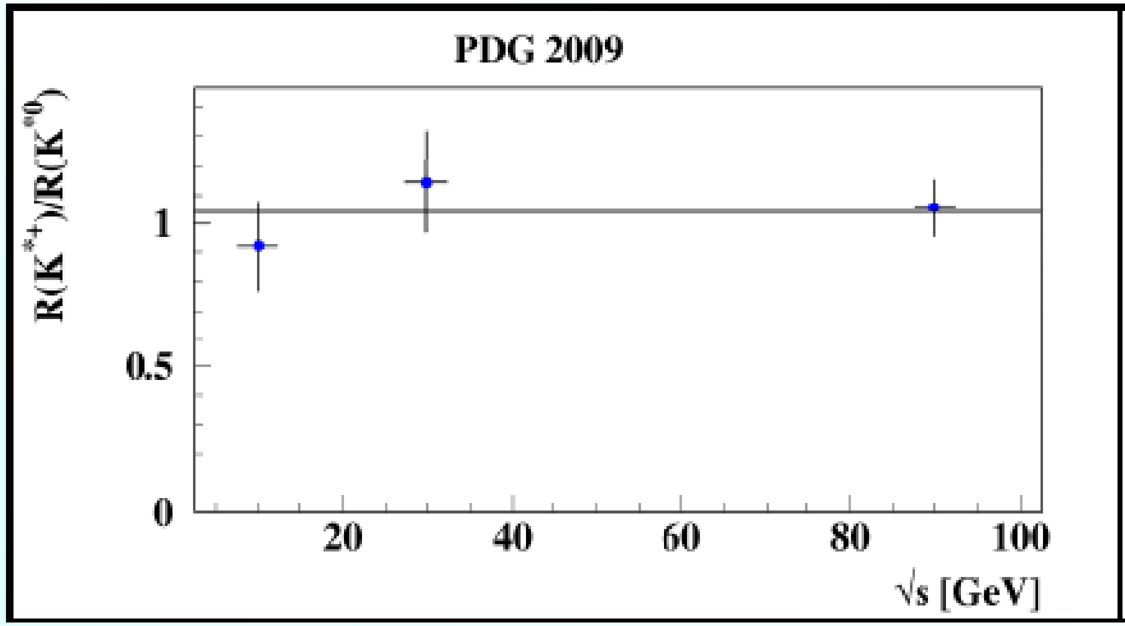
- We also select decay $K^{*+} \to K_S\pi^+$;
- We have:

$$\boxed{N_{K^{*+}} = N_{K_S} R(K^{*+})\varepsilon_c}$$

  – $R(K^{*+})$ is the fraction of K_S mesons from $K^{*+} \to K_S\pi^+$ decay;
  – ε_c is the efficiency to reconstruct an additional pion;



Measurement of f_K, F_K



- $R(K^{*+}) = R(K^{*0})$ due to isospin invariance:
  - verified with the available data on production of K^{*+} and K^{*0} in jets at different energies (PDG);
  - Also confirmed by simulation;
  - Related systematic uncertainty 7.5%
- $\varepsilon_0 = \varepsilon_c$ because the same criteria are used to select the pion in $K^{*+} \to K_S \pi^+$ and $K^{*0} \to K^+ \pi^-$
  - Verified in simulation;
  - Related systematic uncertainty 3%;

Measurement of f_K, F_K

- With these conditions applied, we obtain f_K , F_K as:

$$f_K = \frac{N(K_S)}{N(K^{*+})} f_{K^{*0}}$$

$$F_K = \frac{N(K_S)}{N(K^{*+})} F_{K^{*0}}$$

  - The same values $N(K_S)$, $N(K^{*+})$ are used to measure f_K , F_K ;
- • We assume that the fraction $R(K^{*0})$ of charged kaons coming from $K^{*0} \rightarrow K^+\pi^-$ decay is the same in the inclusive muon and like-sign dimuon sample;
  - We verified this assumption in simulation;
- We assign the systematic uncertainty 3% due to this assumption;

Measurement of f_π, F_π

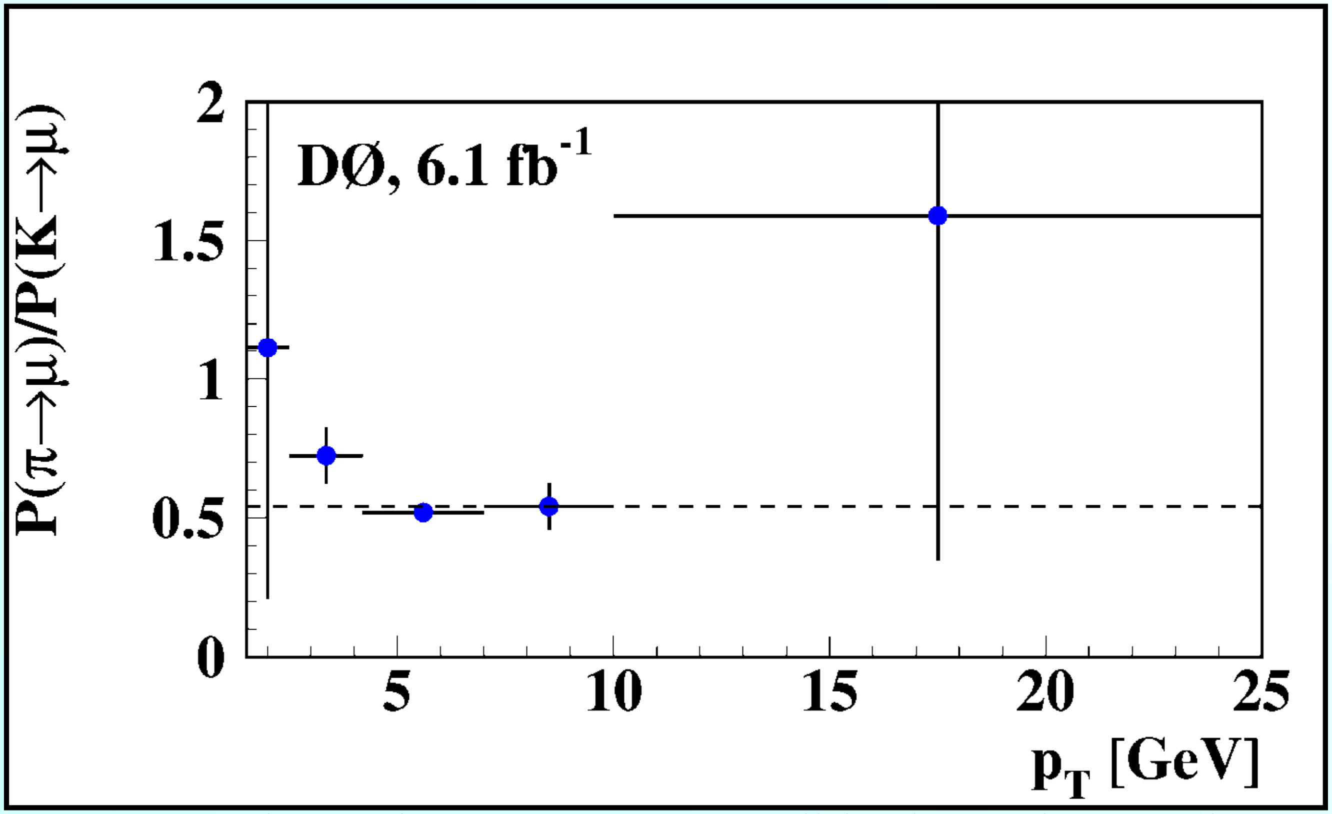
- We use as an input:
  - Measured fractions f_K , F_K;
  - Ratio of multiplicities of pion and kaon n_π / n_K in QCD events taken from simulation;
  - Ratio of multiplicities of pion and kaon N_π / N_K in QCD events with one additional muon taken from simulation;
  - Ratio of probabilities for charged pion and kaon to be identified as a muon: $P(\pi \to \mu) / P(K \to \mu)$;
  - Systematic uncertainty due to multiplicities: 4%
- • We obtain f_π , F_π as:

$$\boxed{\begin{aligned} f_\pi &= f_K \frac{P(\pi \to \mu)}{P(K \to \mu)} \frac{n_\pi}{n_K} \\ F_\pi &= F_K \frac{P(\pi \to \mu)}{P(K \to \mu)} \frac{N_\pi}{N_K} \end{aligned}}$$

Measurement of P(π→μ)/ P(K→μ)

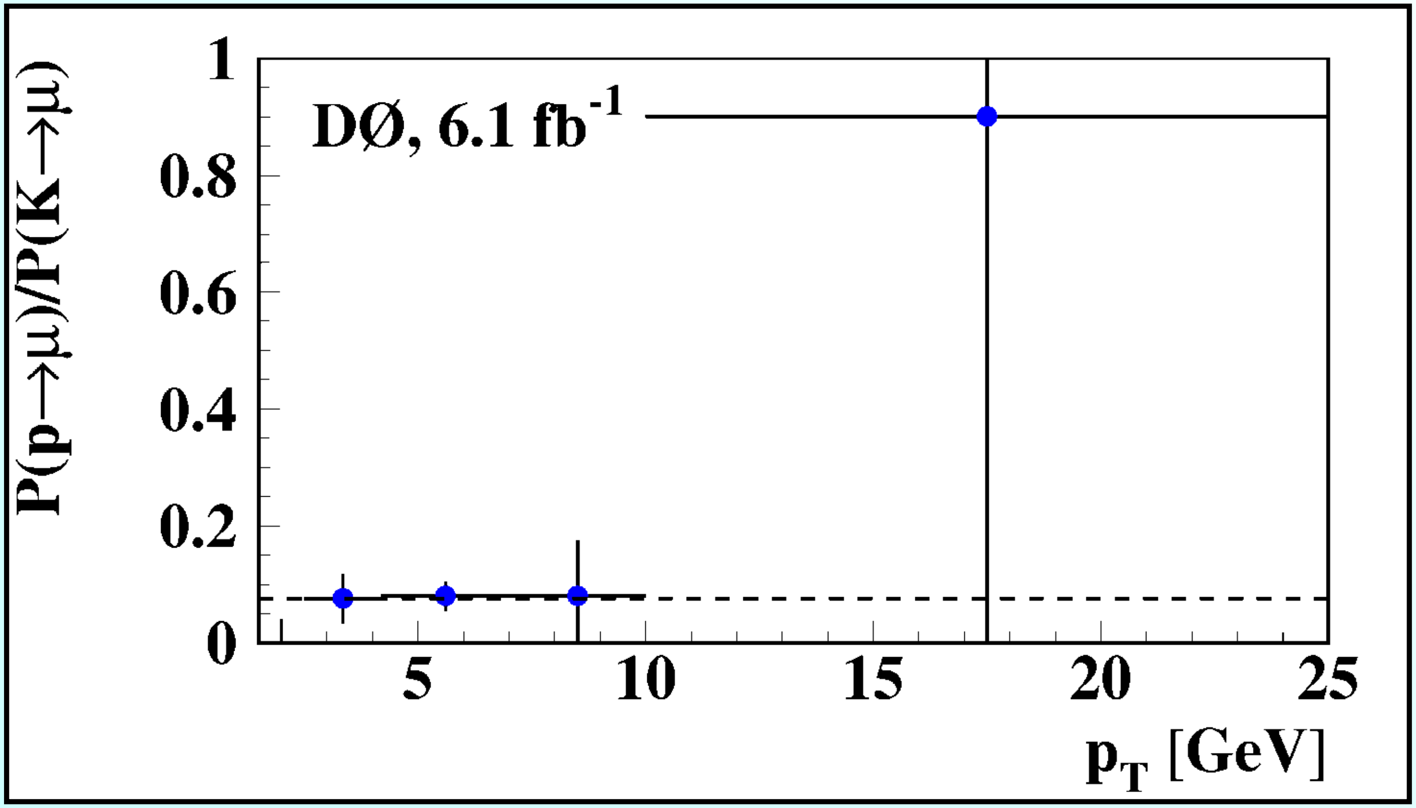
- The ratio of these probabilities is measured using decays $K_S \to \pi^+ \pi^-$ and $\phi(1020) \to K^+ K^-$;
- We obtain:

$$\boxed{P(\pi \to \mu) / P(K \to \mu) = 0.540 \pm 0.029}$$



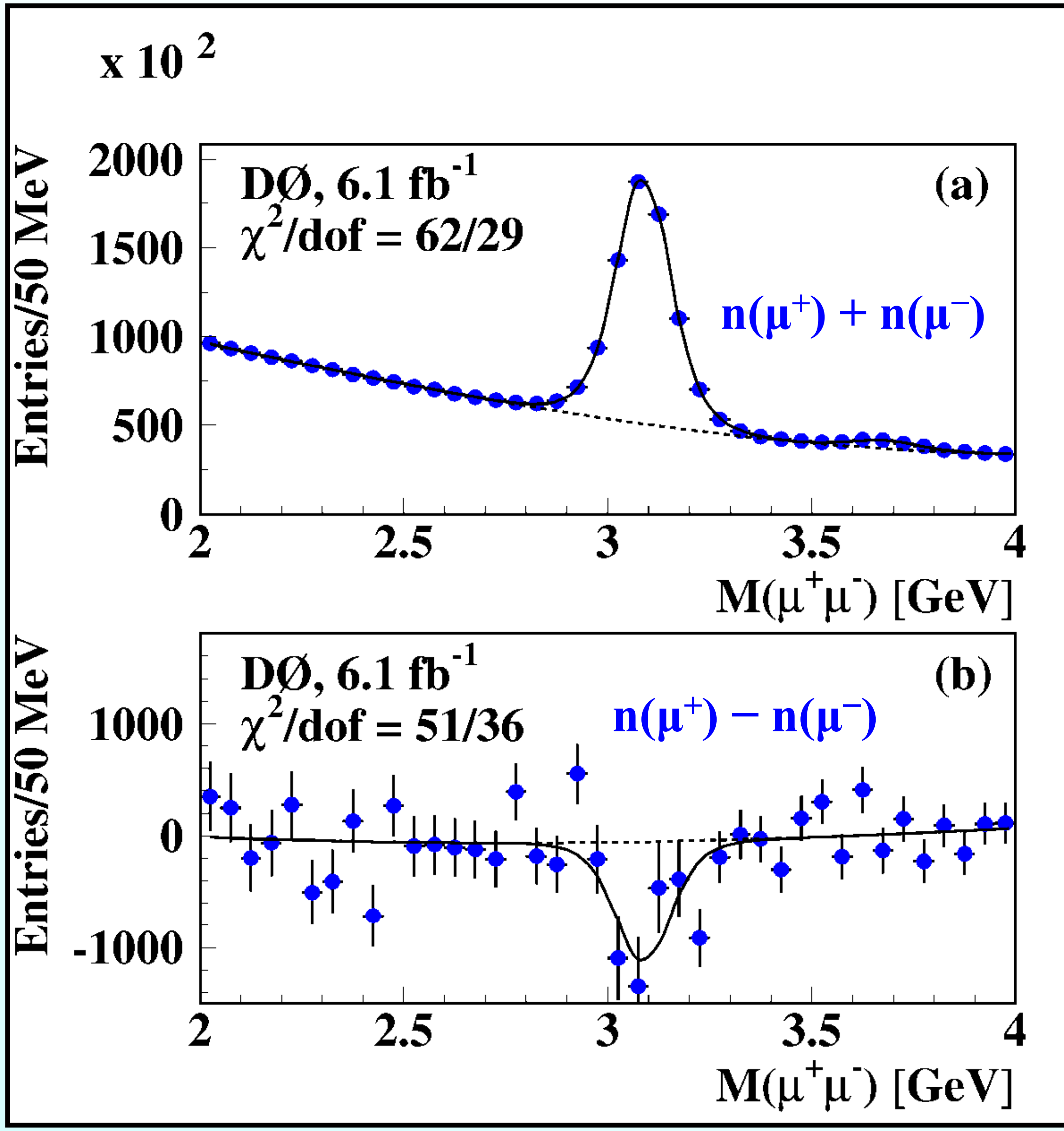
Measurement of f_p, F_p

- Similar method is used to measure the fractions f_p , F_p ;
- The decay $\Lambda \to p\pi^-$ is used to identify a proton and measure $P(p\to\mu)/P(K\to\mu)$;
- We obtain: $\boxed{P(p \to \mu)/P(K \to \mu) = 0.076 \pm 0.021}$



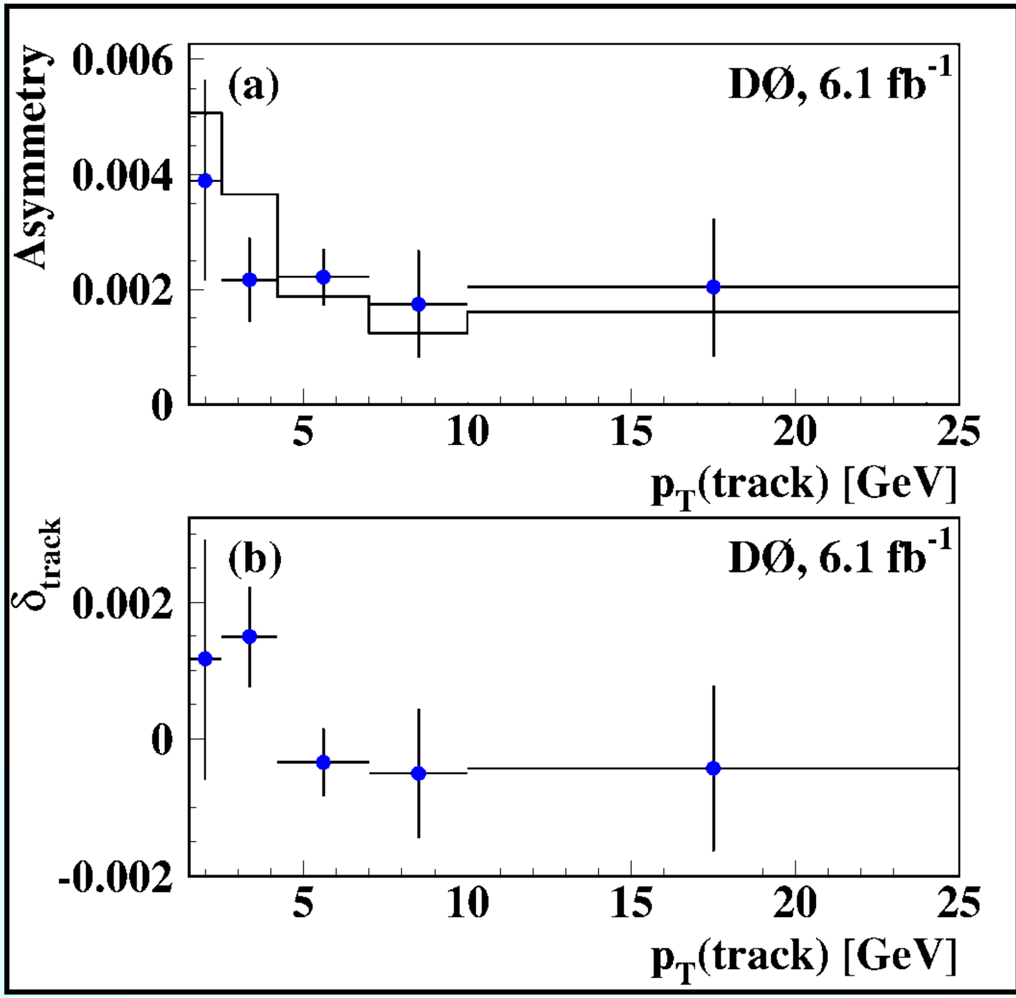
Muon reconstruction asymmetry

- We measure the asymmetry of muon reconstruction using decays $J/\psi \to \mu^+\mu^-$;
  - Select events with only one identified muon and one additional track;
  - Build J/ψ meson in these events;
  - Extract muon reconstruction asymmetry from the asymmetry in the number of events with positive and negative muon;



Track reconstruction asymmetry

- We measure track reconstruction asymmetry using events with one muon and 1 additional track;
- We compute the expected track asymmetry using the same method as in the main analysis, and we compare it with the observed asymmetry;
- The difference $\delta = a_{trk} - a_{exp}$ corresponds to a possible residual track reconstruction asymmetry;



- We find the residual track reconstruction asymmetry consistent with zero:

$$\boxed{\delta = (+0.011 \pm 0.035)\%}$$

Processes contributing to *a* and *A*

$$c\,A_{sl}^{b} = a - a_{bkg}$$
$$C\,A_{sl}^{b} = A - A_{bkg}$$

$$a \equiv \frac{n^{+} - n^{-}}{n^{+} + n^{-}}$$

$$A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

Process	a	A
$\overline{B}_q^0 \to B_q^0 \to \mu^+ X$	Yes	Yes
$b \to c \to \mu^+ X$	Yes	Yes
$B \to \mu^+ X$ (without oscillation)	Yes	No
$c \to \mu^+ X$	Yes	No

- All processes except $\overline{B}_q^0 \to B_q^0 \to \mu^+ X$ don't produce any charge asymmetry, but rather dilute the values of a and A by contributing in the denominator of these asymmetries;

Processes contributing to *a* and *A*

	Process	Weight
T_1	$b \to \mu^- X$	$w_1 \equiv 1.$
T_{1a}	$b \to \mu^- X$ (nos)	$w_{1a} = (1-\chi_0)w_1$
T_{1b}	$\bar{b} \to b \to \mu^- X$ (osc)	$w_{1b} = \chi_0 w_1$
T_2	$b \to c \to \mu^+ X$	$w_2 = 0.113 \pm 0.010$
T_{2a}	$b \to c \to \mu^+ X$ (nos)	$w_{2a} = (1-\chi_0)w_2$
T_{2b}	$\bar{b} \to b \to c \to \mu^+ X$ (osc)	$w_{2b} = \chi_0 w_2$
T_3	$b \to c\bar{c}q$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$	$w_3 = 0.062 \pm 0.006$
T_4	$\eta, \omega, \rho^0, \phi(1020), J/\psi, \psi' \to \mu^+\mu^-$	$w_4 = 0.021 \pm 0.001$
T_5	$b\bar{b}c\bar{c}$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$	$w_5 = 0.013 \pm 0.002$
T_6	$c\bar{c}$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$	$w_6 = 0.660 \pm 0.077$

Consistency tests

- Test A: Using only the part of the data sample corresponding to the first 2.8 fb^{-1}.
- Test B: In addition to the reference selections, requiring at least three hits in muon wire chamber layers B or C, and the χ^2 for a fit to a track segment reconstructed in the muon detector to be less than 8.
- Test C: Since the background muons are produced by decays of kaons and pions, their track parameters measured by the central tracker and by the muon system are different. Therefore, the fraction of background strongly depends on the χ^2 of the difference between these two measurements. The requirement on this χ^2 is changed from 40 to 4 in this study.

Consistency tests (cont.)

- Test D: The requirement on the transverse impact parameter is changed from 0.3 to 0.05 cm, and the requirement on the longitudinal distance between the point of closest approach to the beam and the associated primary vertex is changed from 0.5 to 0.05 cm (this test serves also as a cross-check against the possible contamination from muons from cosmic rays in the selected sample).
- Test E: Using only low-luminosity events with fewer than three primary vertices.
- Test F: Using only events with the same polarities of the solenoidal and toroidal magnets.

Consistency tests (cont.)

- Test G: Changing the requirement on the invariant mass of the two muons from 2.8 GeV to 12 GeV.
- Test H: Using the same muon p_T requirement, $p_T > 4.2$ GeV, over the full detector acceptance.
- Test I: Requiring the muon p_T to be $p_T < 7.0$ GeV.
- Test J: Requiring the azimuthal angle ϕ of the muon track be in the range $0 < \phi < 4$ or $5.7 < \phi < 2\pi$. This selection excludes muons directed to the region of poor muon identification efficiency in the support structure of the detector.

Consistency tests (cont.)

- Test K: Requiring the muon η be in the range $|\eta| < 1.6$ (this test serves also as a cross-check against the possible contamination from muons associated with the beam halo).
- Test L: Requiring the muon η be in the range $|\eta| < 1.2$ or $1.6 < |\eta| < 2.2$.
- Test M: Requiring the muon η be in the range $|\eta| < 0.7$ or $1.2 < |\eta| < 2.2$.
- Test N: Requiring the muon η be in the range $0.7 < |\eta| < 2.2$.

Consistency tests (cont.)

- Test O: Using like-sign dimuon events passing at least one single muon trigger, while ignoring the requirement of a dimuon trigger for these events.
- Test P: Using like-sign dimuon events passing both single muon and dimuon triggers.